AFES

SOCIETY OF PETROPHYSICISTS AND WELL LOG ANALYSTS

HERIOT WATT UNIVERSITY

Basic Concepts in Well Testing for Reservoir Description

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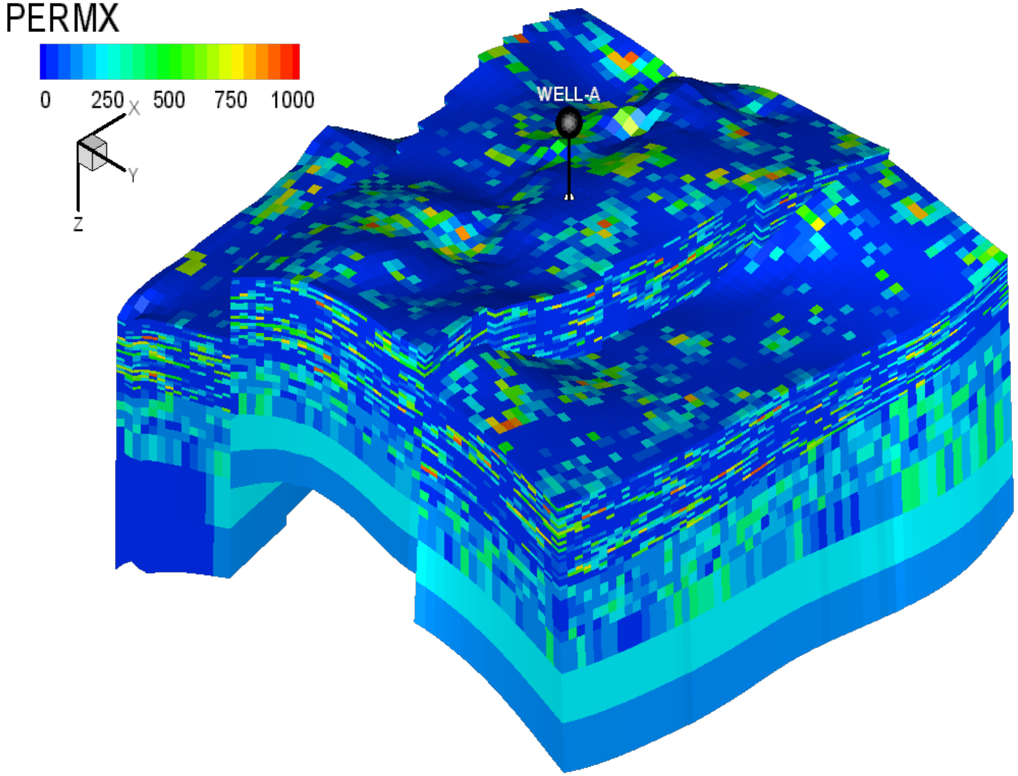
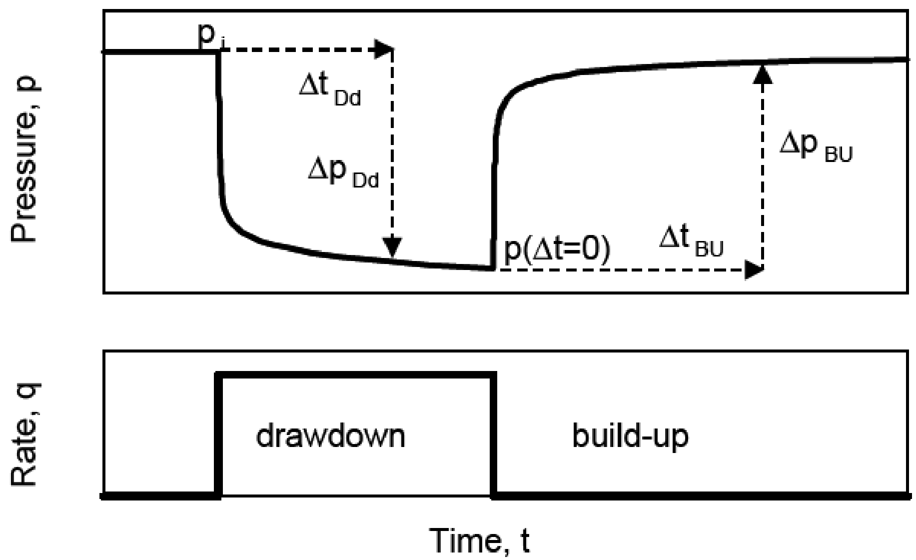
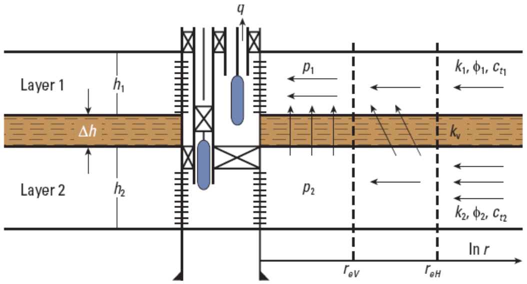


Introduction

Description of a well test



Flow rate @ Surface
Pressure @ Down-hole



Schlumberger 2002

$$\Delta P_{DD} = P_i - P(t)$$
$$\Delta P_{BU} = P(t) - P(\Delta t = 0)$$

1. During a well test, a transient pressure response is created by a temporary change in production rate.
2. For well evaluation→ less than two days.

reservoir limit testing →several months of pressure data

Well test objectives

- Exploration well
  - On initial well, confirm HC existence, predict a first production forecast (DST: fluid nature, Pi, reservoir properties
- Appraisal well
  - Refine previous interpretation, PVT sampling, (longer test: production testing)
- Development well
  - On production well, satisfy need for well treatment, interference testing, P_{av}

Well test Types

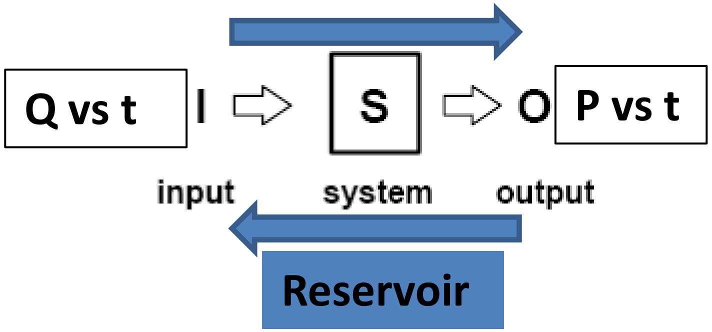
- Draw down
  - Open the well with constant rate→ decreasing bottom hole pressure
- Build Up test
  - Shut-in the well → increasing bottom hole pressure
- Injection/ fall-off test (different fluid type)
  - The fluid is injected → increasing Bottom hole pressure
  - Shut-in the well → decreasing the bottom hole pressure
- Interference test / pulse test
  - Producing well → measure pressure in another shut-in well away from the producer→ communication test
- Gas well test
  - Back pressure , Isochronal test , modified isochronal test → well productivity, AOFP, Non-Darcian skin.

Information obtained from well testing

- Well Description
  - For completion interval (s),
  - Production potential (PI), and skin
- Reservoir Description
  - "Average" permeability (horizontal and vertical)
  - Heterogeneities(fractures, layering, change of Prop.)
  - Boundaries (distance and "shape")
  - Pressure (initial and average)
- Note: Well Description and Reservoir Description
  - May be separate objectives

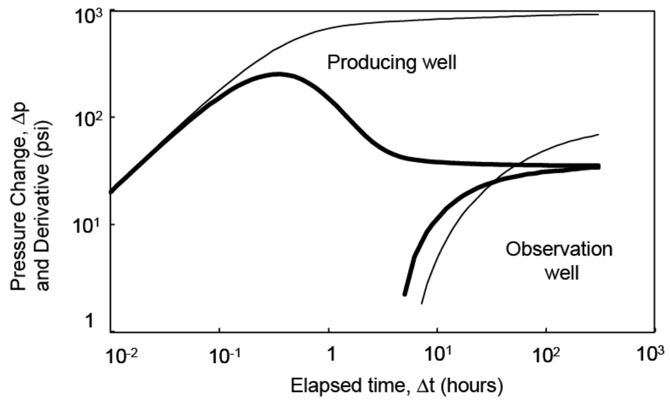
Methodology

- The inverse problem



- Model recognition (S)
  - Well test models are different from the geomodels in the sense that they are dynamic models and also it's an average model.

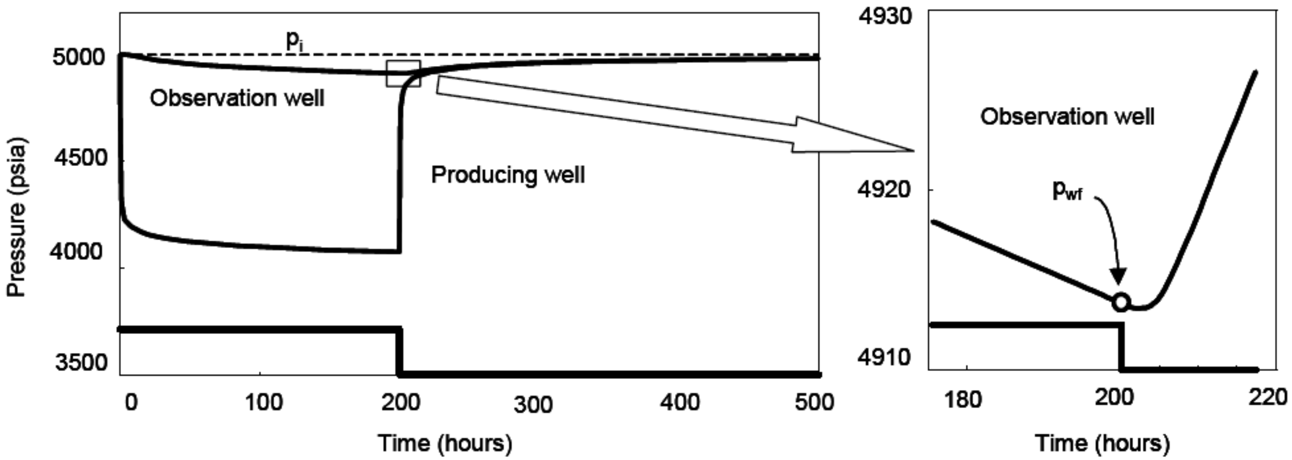
Example: Interference test

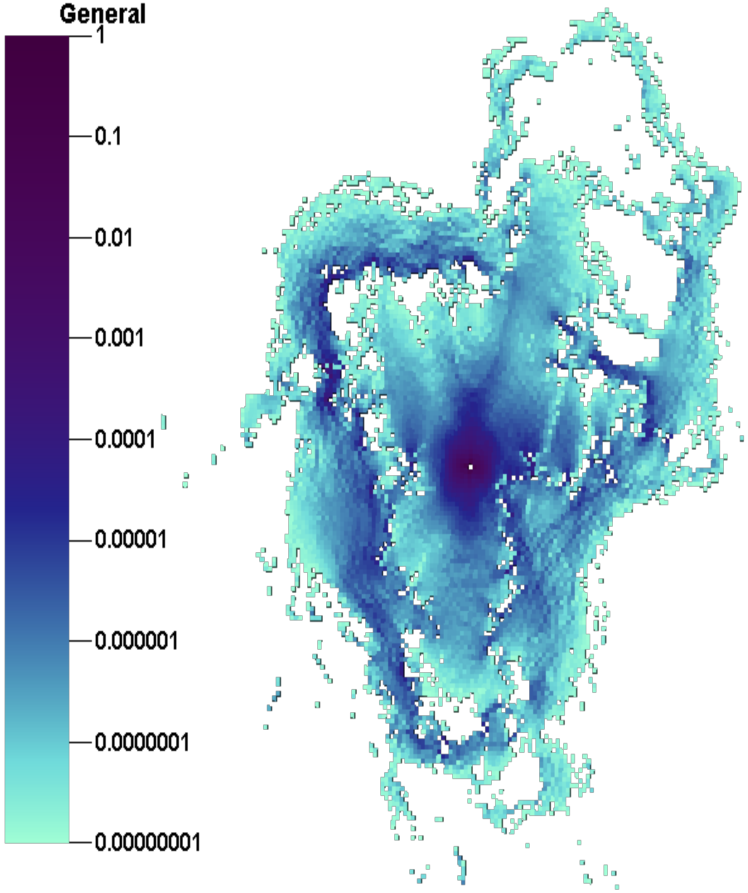


1. Create signal at producing well
2. Measure the signal at both wells

Observation well:

1. The signal will be received with a delay
2. The response is smaller





Fluid Flow Equation

concepts

- Permeability and porosity
- Storativity and Transmissibility
- Skin
- Wellbore storage
- Radius of investigation
- Superposition theory
- Flow regimes
- Productivity index (PI)

Concepts-Definitions

- Permeability:
  - The absolute permeability is a measure of the capacity of the medium to transmit fluids. Unit: md (10^{-12} m^2)
- Transmissibility $T = \dfrac{Kh}{\mu}$
- Storativity $S = \varphi c_t h$
- Diffusivity (Hydraulic diffusivity) $\eta = \dfrac{T}{S}$
- AOF
- PI

Fluid flow equation: ingredients

- Conservation of mass (continuity equation)

$$\nabla(\rho \bullet \vec{v}) = -\frac{\partial}{\partial t}(\rho\phi)$$

- EOS, defining the density and changes in density with pressure

$$c = \frac{1}{\rho}\frac{\partial \rho}{\partial t}$$

- Transport equation (Darcy’s law: experimental, or Navier-Stoke)

$$\vec{v} = -\frac{1}{\mu}\underline{\underline{\mathbf{K}}} \bullet \nabla P$$

Fluid flow equation: radial case

- Continuity + Darcy: in radial coordinate (isotropic)

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{r\rho k_r}{\mu}\frac{\partial P}{\partial r}\right)=\frac{\partial}{\partial t}(\varphi\rho)$$

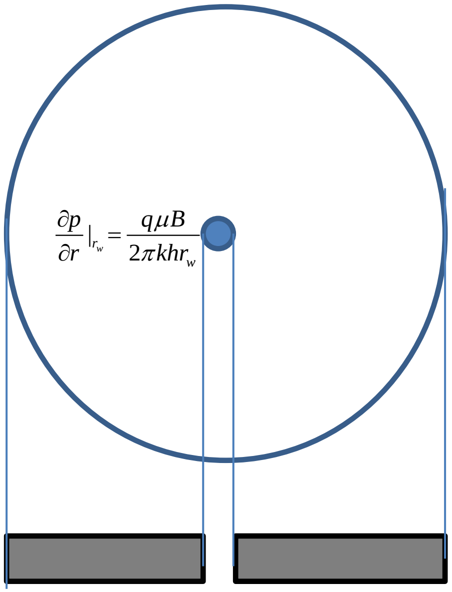
- Assumptions:

  Radial flow into a well opened over entire thickness , single phase, slightly compressible fluid, constant viscosity , ignoring the gravity, constant permeability and porosity

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P}{\partial r}\right)=\frac{\varphi\mu c}{k}\frac{\partial P}{\partial t}$$

Solution to radial diffusivity equation

- Inner/outer Boundary conditions:



1. Constant Pressure boundary, p=pi @re
2. Infinite reservoir p=pi @ ∞
3. No flow boundary ∂p/∂r =0 @ re

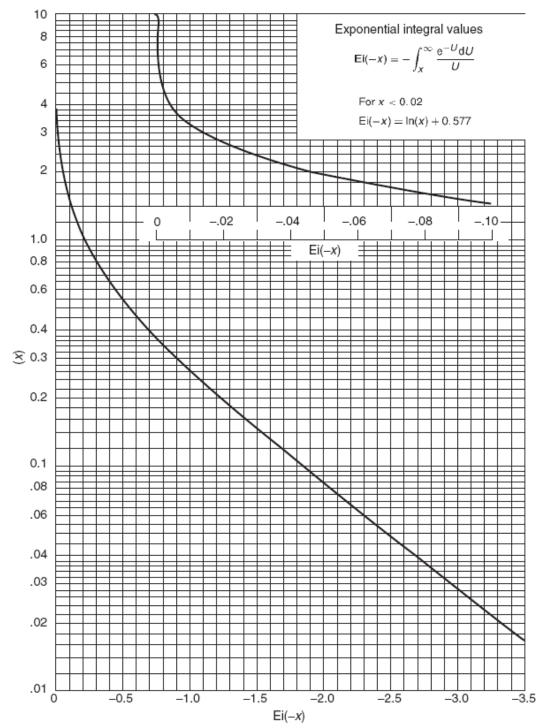
Unsteady- Infinit acting reservoirs(radial flow regime): DD

- Finite diameter well without WBS- infinite acting reservoir

$$\Delta P(r,t)=\frac{q}{2\pi T}\frac{2}{\pi}\int_0^{\infty}\left(1-e^{-u^2 t_D}\right)\frac{J_1(u)Y_0(u\bar{r})-Y_1(u)J_0(u\bar{r})}{u^2\left(J_1^2(u)+Y_1^2(u)\right)}du$$

$$P(r,t)=P_i-\frac{q\mu B}{2\pi kh}\left(\frac{1}{2}Ei\left(-\frac{\varphi\mu c r^2}{4kt}\right)\right)$$

$$P_i-P_{wf}(t)=\frac{162.6q\mu B}{Kh}\left(\log\left(\frac{kt}{\varphi\mu c_t r_w^2}\right)-3.23+0.87S\right)$$



USS,PSS,SS?

∂P/∂t=f(x,t) → USS (Well test)

∂P/∂t=cte→ PSS (boundary)

∂P/∂t=0 → SS(aquifer)

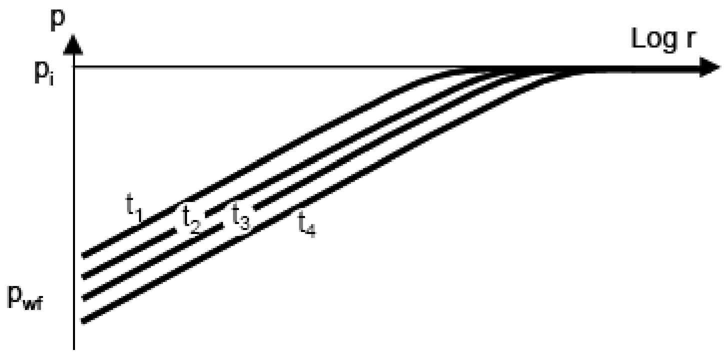
Radius of investigation

The radius of investigation *ri tentatively describes the distance that the pressure* transient has moved into the formation.

$$r_i = \mathbf{0.032}\sqrt{\frac{k\Delta t}{\varphi\mu c_t}}$$

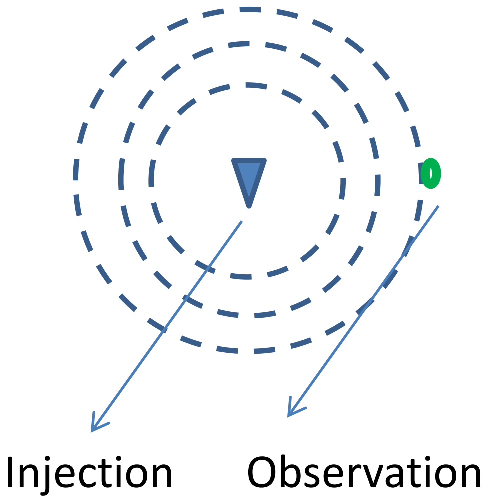
Or it's the radius beyond which the flux should not exceed a specified fraction or percentage of the well bore flow rate

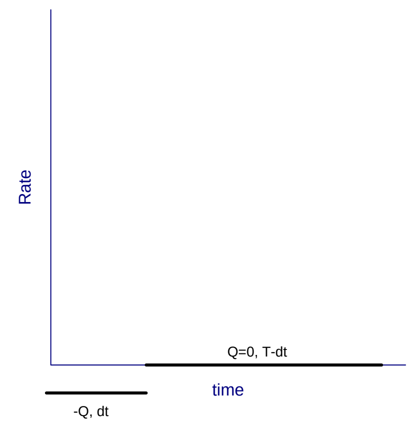
Can we use the radius of investigation to calculate the pore volume and reserve?

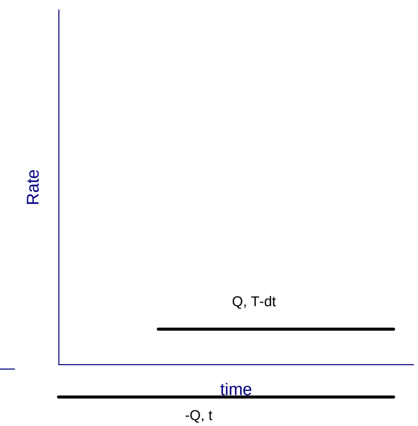


1. Based on radial homogeneous→ if fracture ?
2. Is it a radius or volume?
3. How about gauge resolution?
4. Which time we are talking about?
5. How about a close system?
6. How about the velocity of front?

Radius of investigation



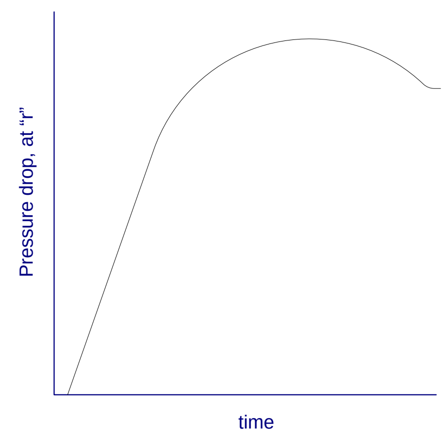




$$\Delta P_{r,t} = \Delta P_{r,t_1} + \Delta P_{r,t_2}$$

$$\Delta P_{r,t_1} = \frac{-70.6(-qB)\mu}{kh} Ei\left(\frac{-948\varphi\mu C_t r^2}{kt}\right)$$

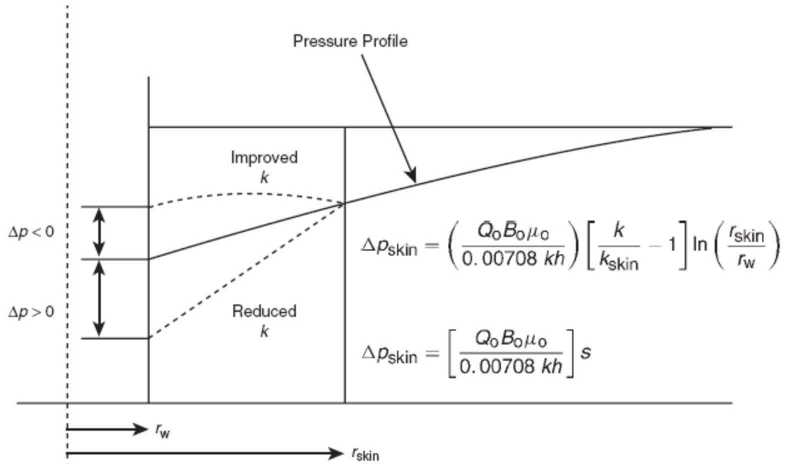
$$\Delta P_{r,t_{12}} = \frac{-70.6(qB)\mu}{kh} Ei\left(\frac{-948\varphi\mu C_t r^2}{k(t-\Delta t)}\right)$$



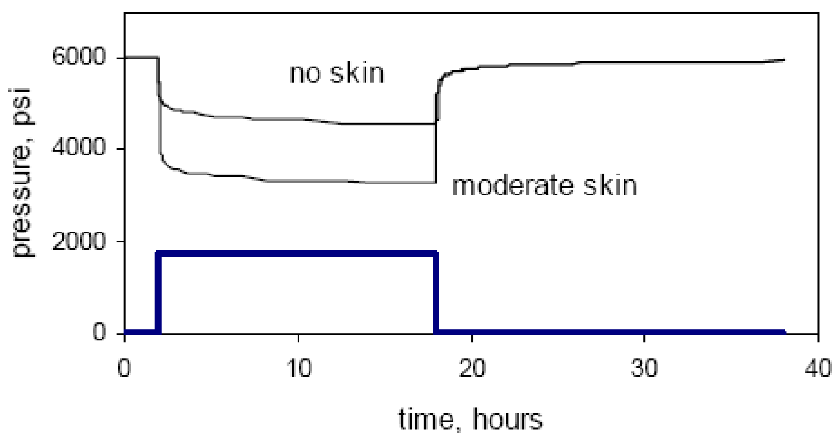
$$\Delta P(r,t) = \frac{-1694.4\mu}{kht} e^{\frac{-948\varphi\mu C_t r^2}{kt}}$$

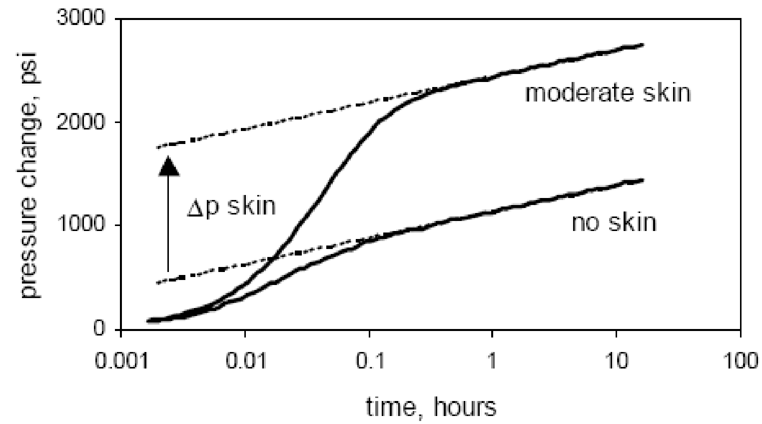
$$t_{max} = \frac{948\varphi\mu C_t r^2}{k}$$

Skin Pressure Drop



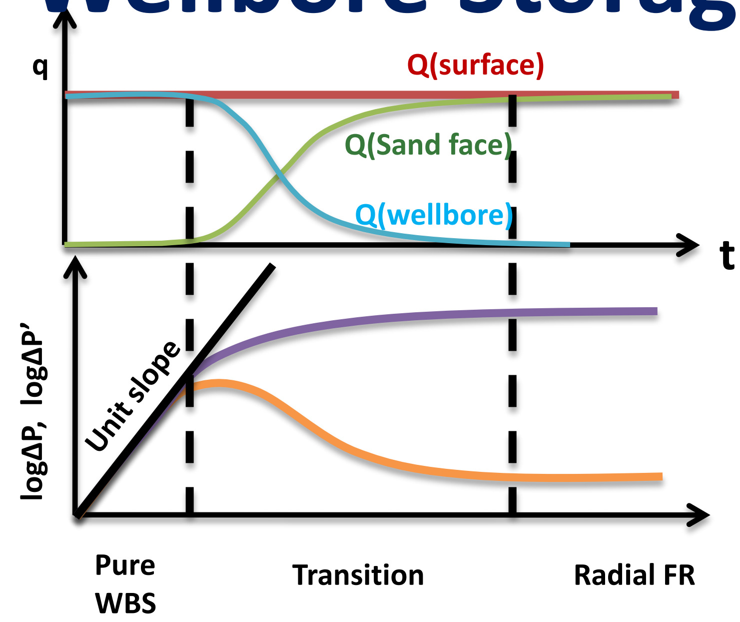
Skin Pressure drop: higher pressure drop near the well bore due to mud filtrate, reduced K , improved K, change of flow streamlines, fluid composition change,…. It is one of the most important parameter used in production engineering as it could refer to a sick or excited well and leads to additional work-over operations.





Bourdet 2002

Wellbore Storage



In surface production or shut in the surface rate is controlled
However due to compressibility of oil inside the well bore we have difference between sandface production and surface production
It can affect the inner boundary condition and make the solution more complicated

$$C = -\frac{\Delta V}{\Delta P} = c_0 V_{wb}$$

$$\Delta P(\Delta t) = \frac{qB}{24C}\Delta t$$

Pure WBS

Superposition

- Effect of multiple well
  - $\Delta P_{tot@well1} = \sum \Delta P_{wells\ @well1}$
- Effect of rate change

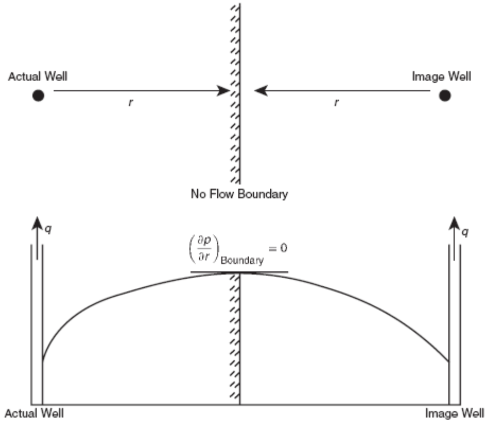
$$\Delta P_{tot} = \Delta P_{(q1-0)} + \Delta P_{(q2-q1)} + \dots + \Delta P_{(q2-q1)@tn-t_{i-1}}$$

$$Sn(\Delta t) = \sum_{i=1}^{n-1} \frac{q_i - q_{i-1}}{q_n - q_{n-1}} \log\left(\left[\sum_{j=1}^{n-1} \Delta t_j - \Delta t\right] - \log \Delta t\right)$$

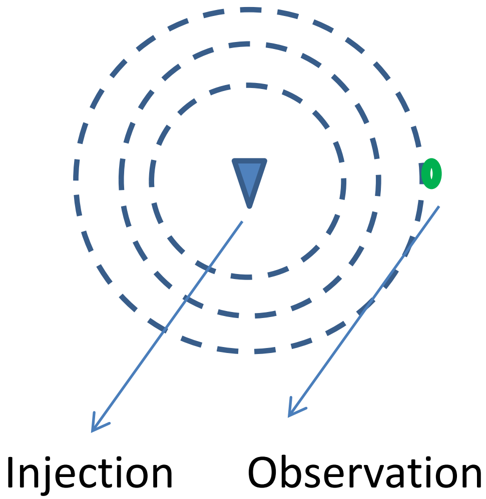
- Effect of boundary

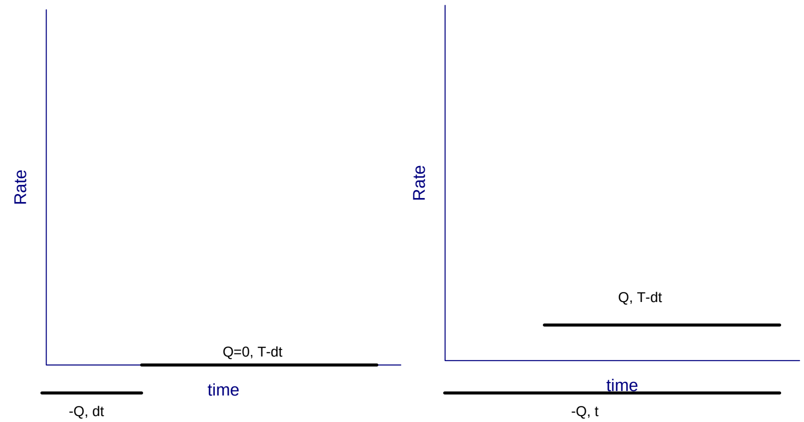
$$\Delta P_{tot} = \Delta P_{act} + \Delta P_{image}$$

- Effect of pressure change



Radius of investigation:superposition





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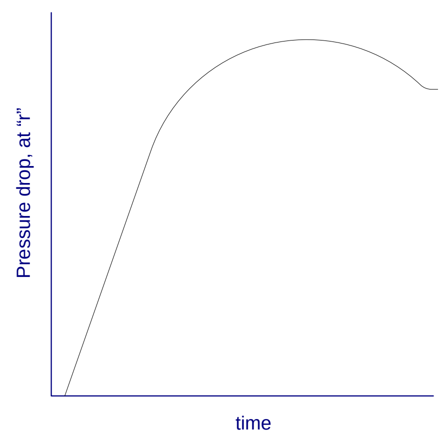
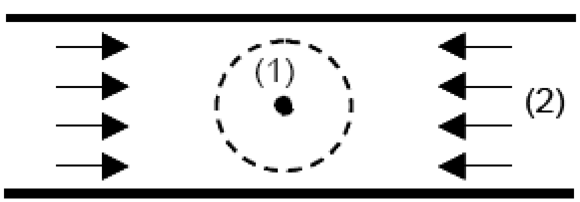
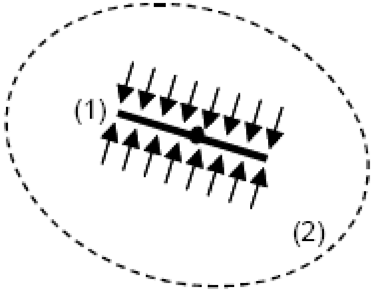
$$t_{\max} = \frac{948\varphi\mu c_t r^2}{k}$$

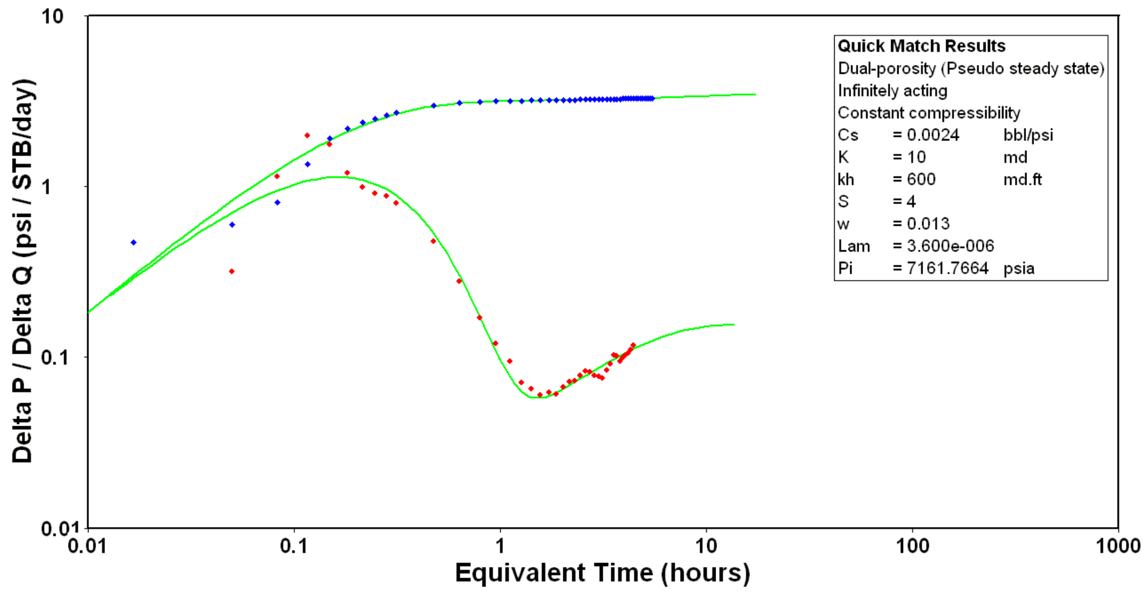


Fluid flow equation : complexity

- Linear , bilinear , radial, spherical
- Depends on the well geometry, and reservoir heterogeneities
- Change the fluid flow equation and the solution
- The fluid heterogeneities affect the diffusivity equation and the solution (non linearity→ gas res)

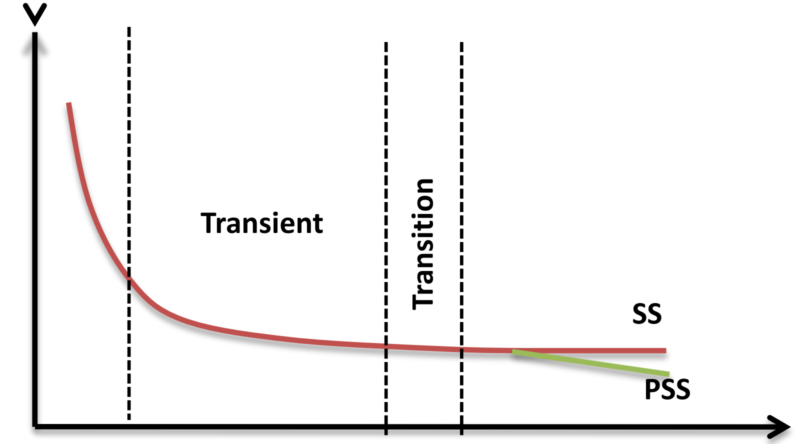


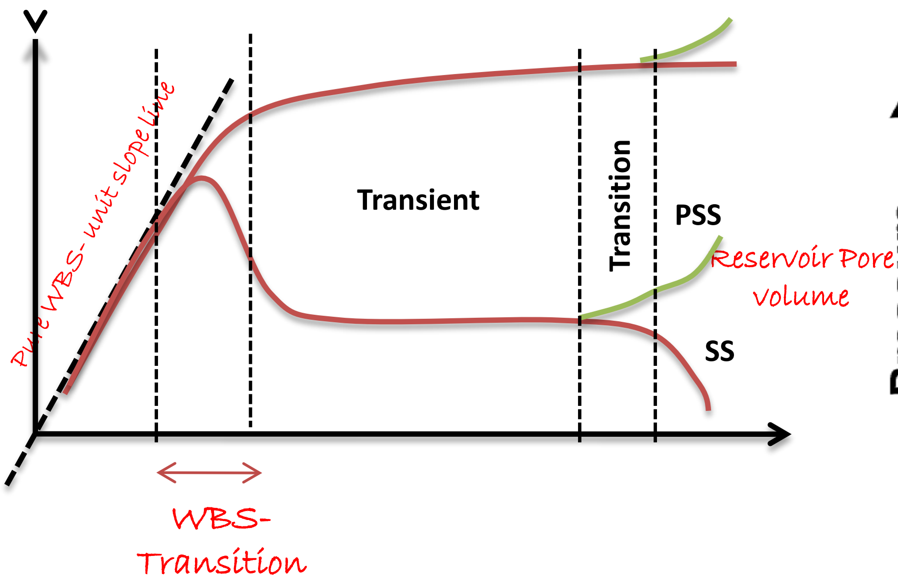




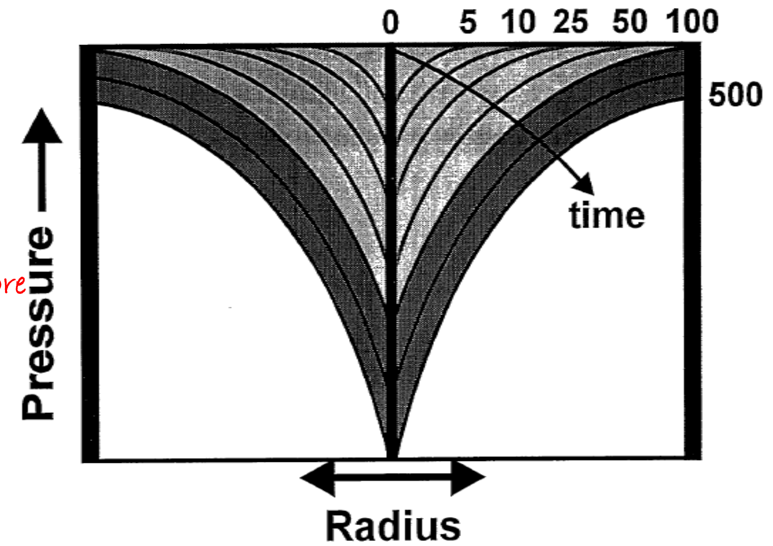
Derivative Plots

Derivative plot





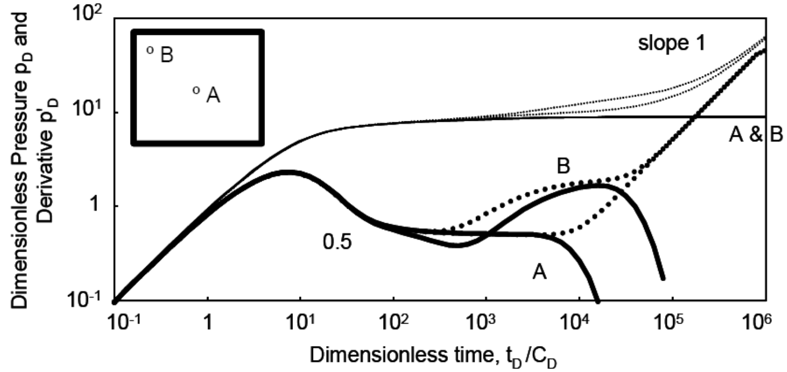
Well	Reservoir	Outer Boundaries
Vertical Horizontal Storage Constant Changing Completion damaged fractured acidized	Homogeneous Heterogeneous Composite Multilayer Dual porosity (fissured)	Infinite Rectangular Circular No-flow Constant-pressure



Matter 2004

Derivative plot : Example1

Structure effect on well testing

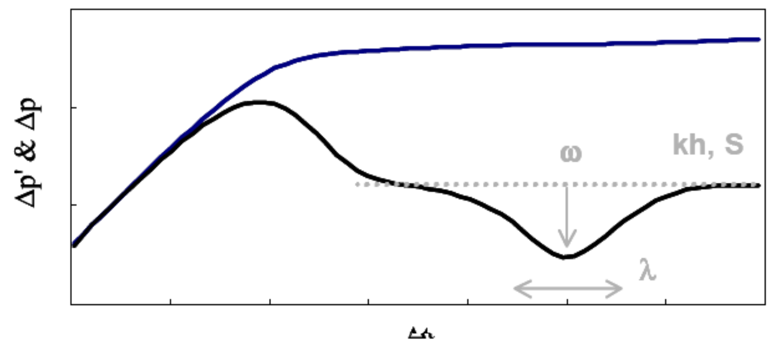


Double porosity, restricted interporosity flow (4.2)

1 Radial fissures, k

2 Transition (storativity ↑), ω and λ

3 Radial fissures + matrix, kh

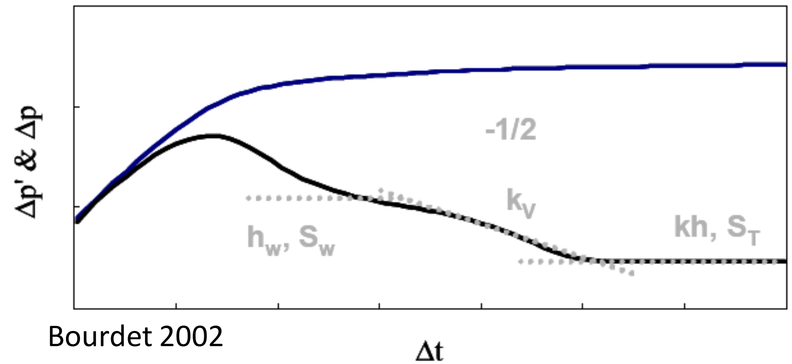


Partial penetration (3.4)

1 Radial, h_w and S_w

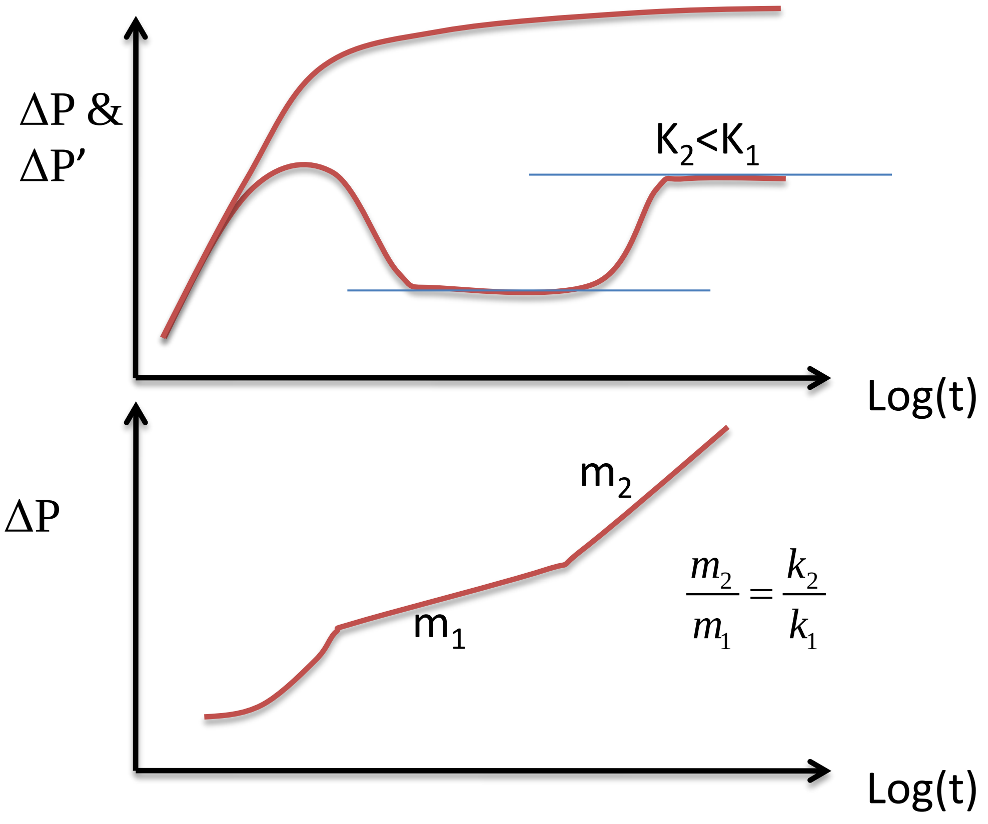
2 Spherical (mobility ↑), k_V

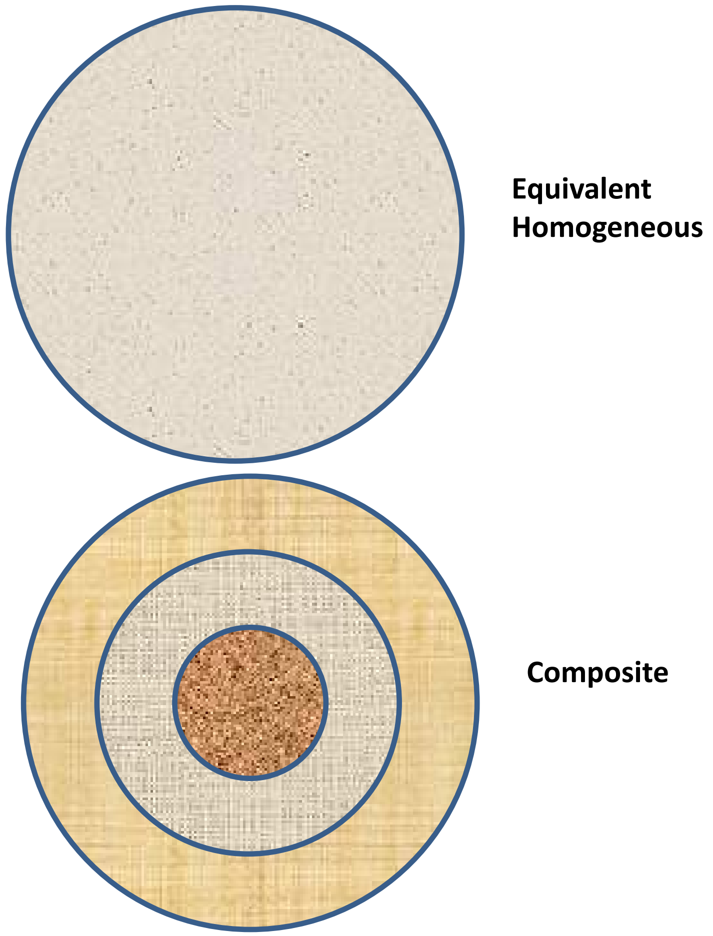
3 Radial, kh and S_T



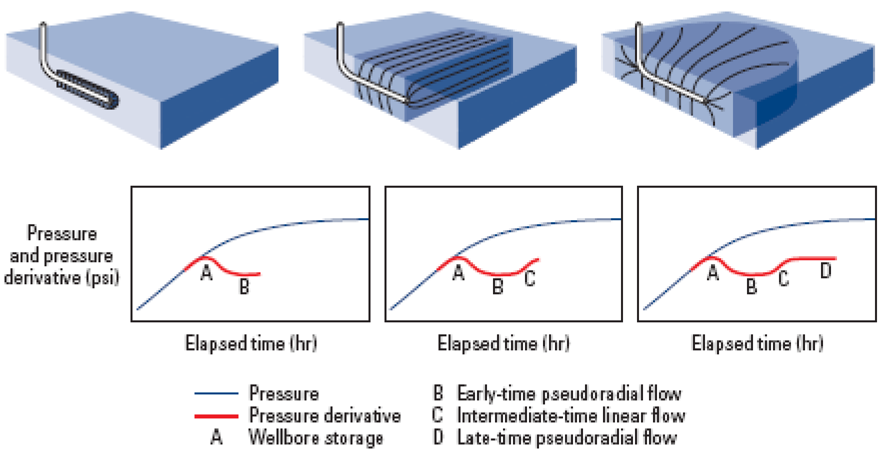
Bourdet 2002

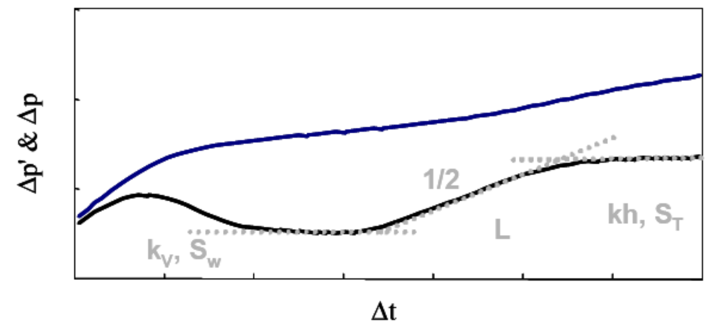
Derivative plot
Example2 : Radial Composite





Derivative plot : Example3 : Horizontal Well Testing





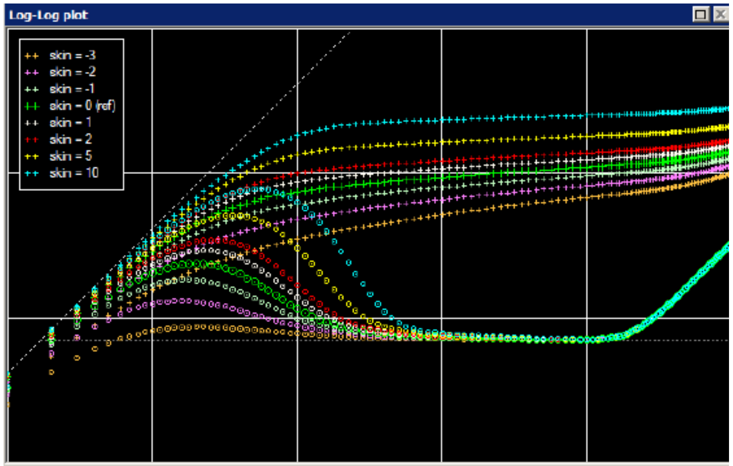
1 Radial vertical, k_V and S_w
2 Linear (mobility ↓), L
3 Radial, kh and S_T

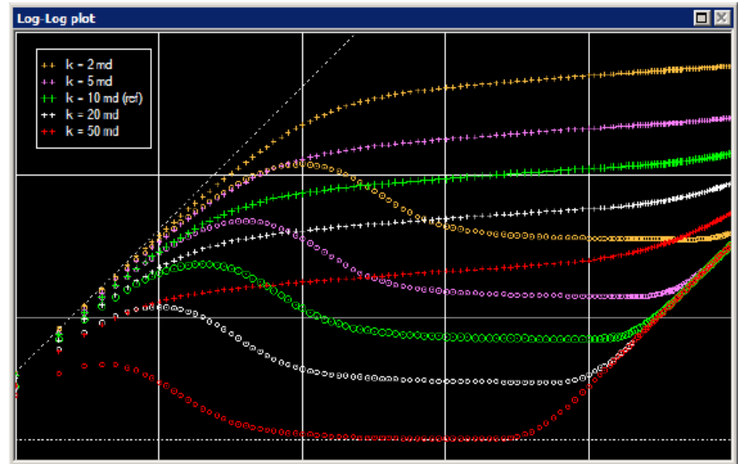
Example: Linear flow:

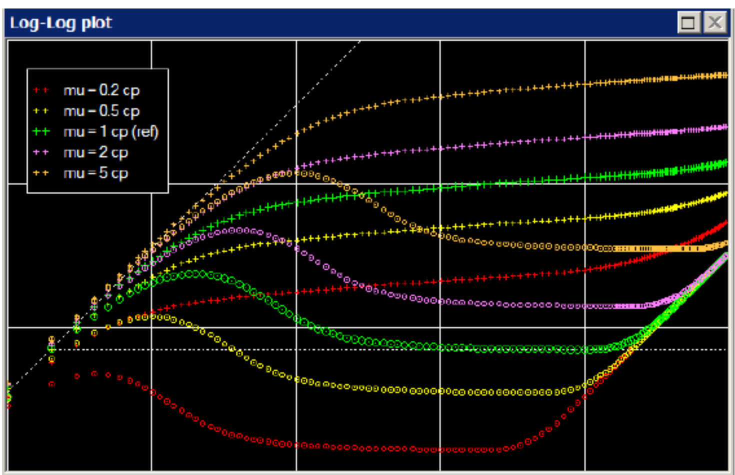
$$\Delta p = \frac{8.128\, qB}{2Lh}\sqrt{\frac{\mu \Delta t}{\phi c_t k_H}} + \frac{141.2\, qB\mu}{2\sqrt{k_V k_H}\, L} S_w + \frac{141.2\, qB\mu}{k_H\, h} S_z$$

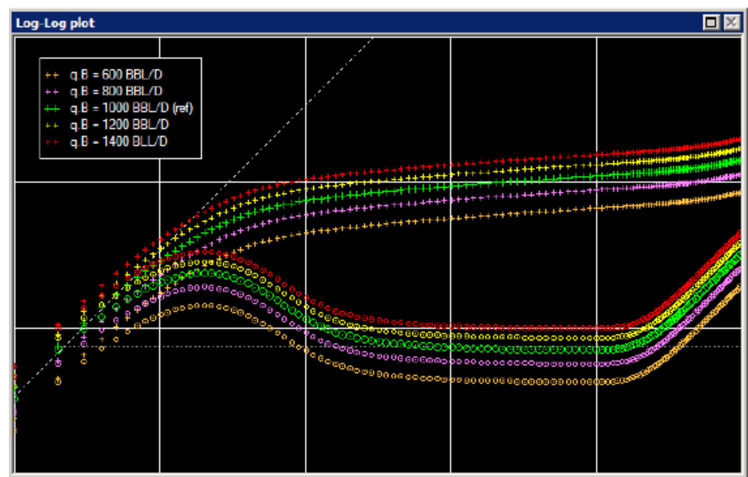
1 Vertical radial → S_w
2 Linear flow → S_{pp}, S_w
3 Later radial flow →
$S_T = f(S_w, S_{pp}, S_w, S_G, \ldots)$

Some sensitivities!









Houze et al. 2007

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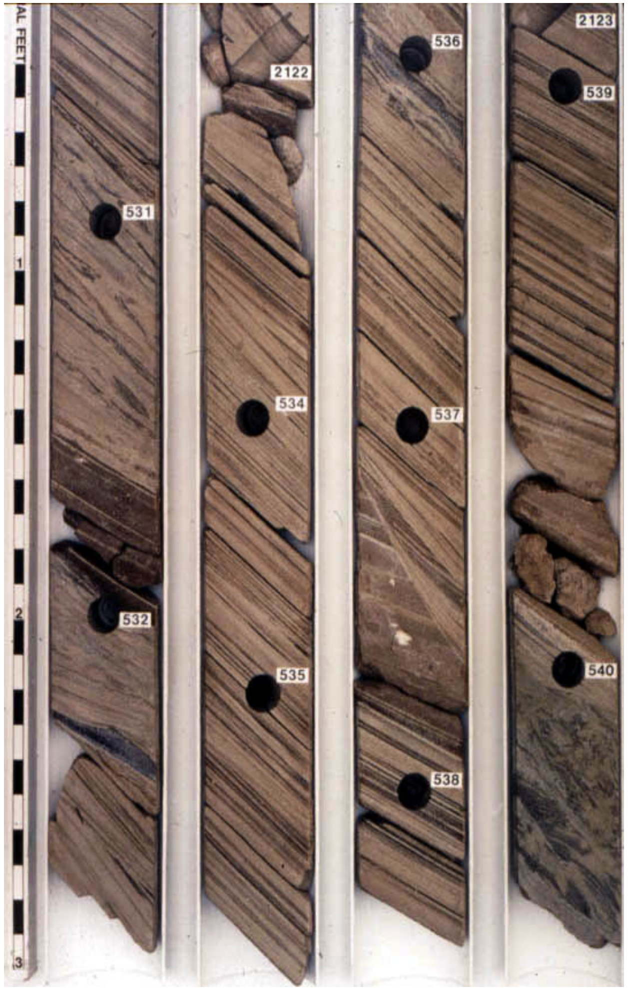
Practical Issues

- Inaccurate rate history
- Shut-in times
- Gauge resolution
- Gauge drift
- Changing wellbore storage
- Phase segregation
- Neighbouring well effect
- Interference
- Tidal effects
- Mechanical noise
- Perforation misties

Uncertain parameters

- Complex permeability / porosity (higher order of heterogeneities)
- Complex thickness
- Complex fluid
- Wellbore effect?
- Any deviation from assumption
- New phenomena ?
- Gauge resolution
- Measurements? Correct rate history
- Numerical- Analytical
- Core-Log values ? Seismic?
- Averaging process?
- Layering response?
- Test design? Sensitivities? Multiple models ?

How to make decision?



Rock Description

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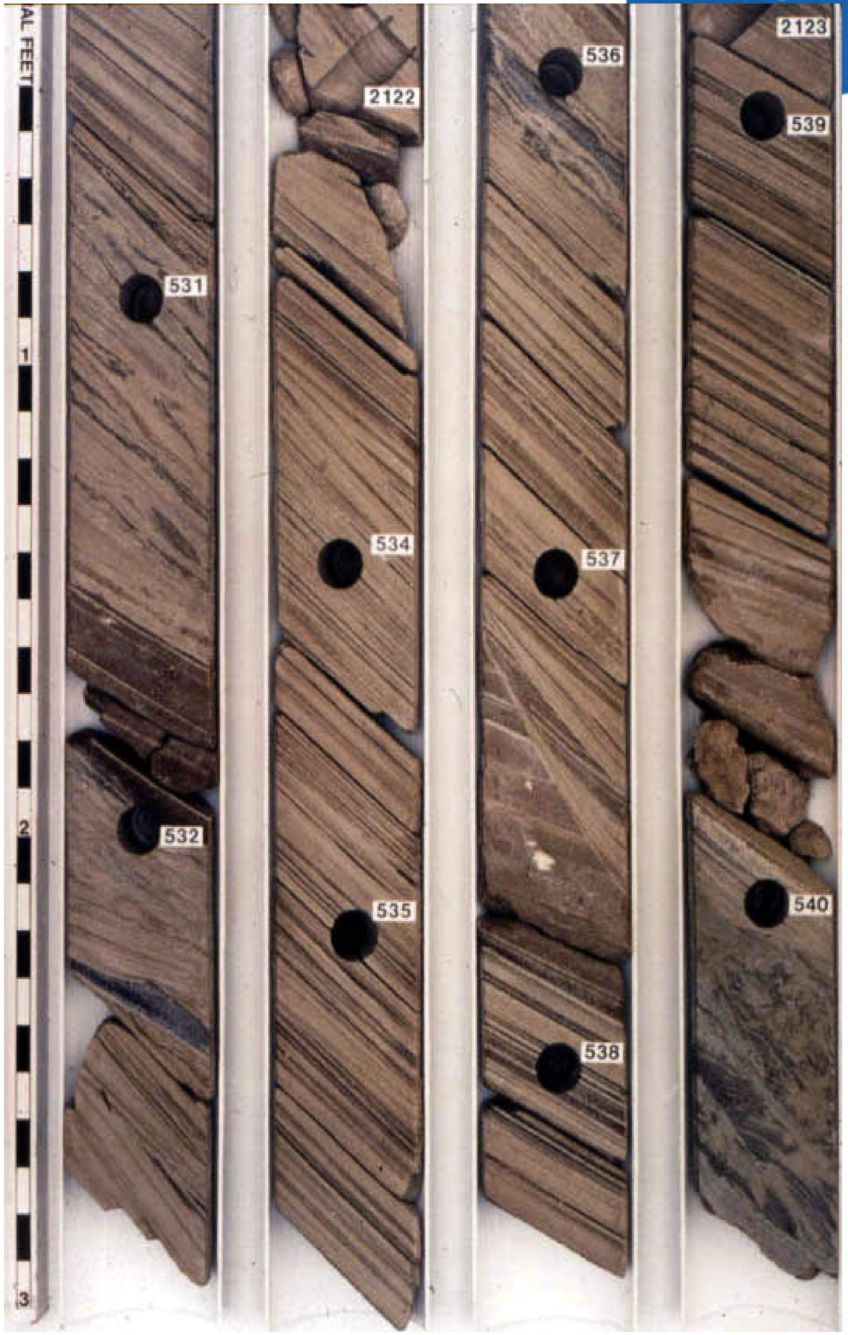
Core data evaluation

- Summary numbers (statistics) for comparison with well tests
- Variability measures
- How do the numbers relate to the geology
- How good are the summary numbers
- How representative are the numbers



Measures of Central Tendency

- Mean - population parameter
- Average - the estimator of the population mean
- Arithmetic average

$$\bar{k}_{ar} = \frac{1}{N}\sum_{i=1}^{N} k_i$$

- Geometric average

$$\bar{k}_{geom} = \left(\prod_{i=1}^{N} k_i\right)^{\frac{1}{N}}$$

$$\bar{k}_{geom} = \exp\left(\frac{1}{N}\sum_{i=1}^{N}\log_e(k_i)\right)$$

- Harmonic average

$$\bar{k}_{har} = N\left(\sum_{i=1}^{N}\frac{1}{k_i}\right)^{-1}$$

Differences between averages

Measures of heterogeneity

$$\bar{k}_{har} \leq \bar{k}_{geom} \leq \bar{k}_{ar}$$

Each permeability average has a different application in reservoir engineering

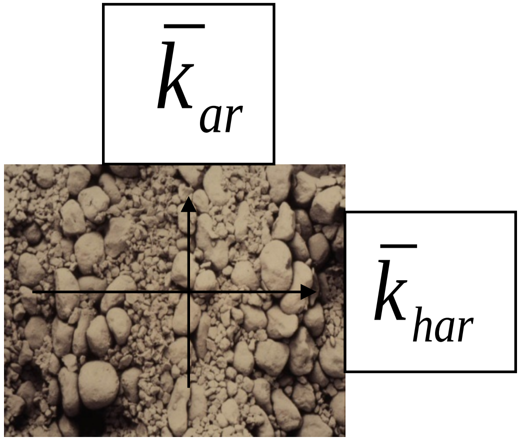
Averages in reservoir engineering

- Used to estimate effective property for certain arrangements of permeability

$\bar{k}_{ar}$ - Horizontal (bed parallel flow)

$\bar{k}_{geom}$ - Vertical and Horizontal (random)

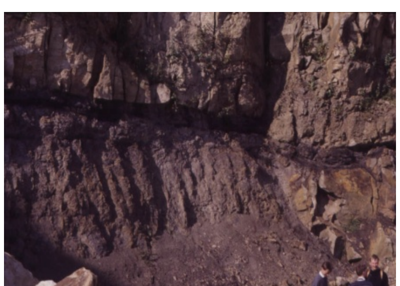
$\bar{k}_{har}$ - Vertical (bed series flow)

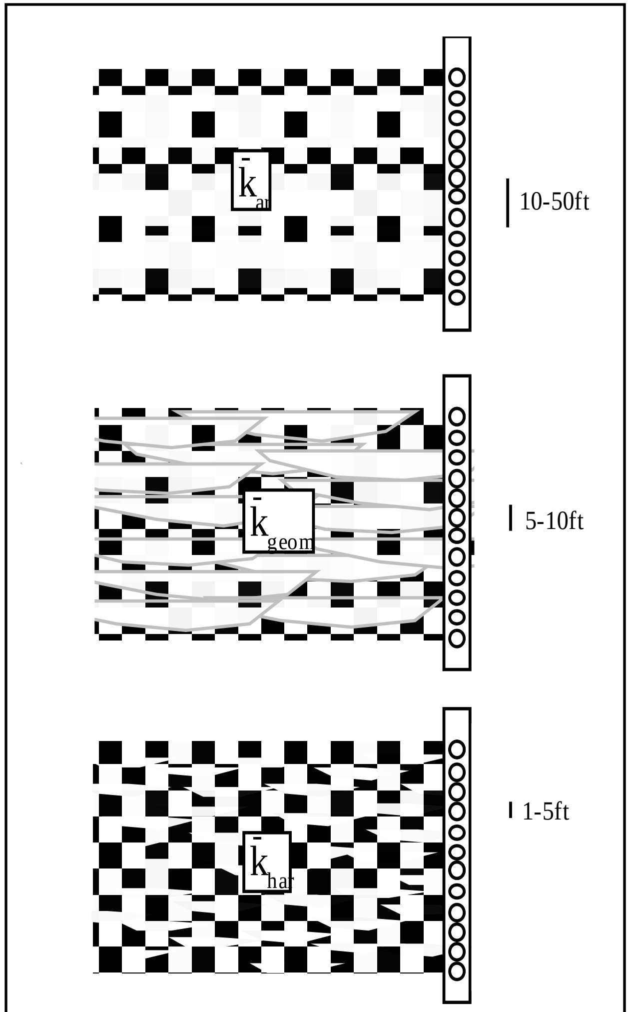


Remember these assumptions….

not the application!!

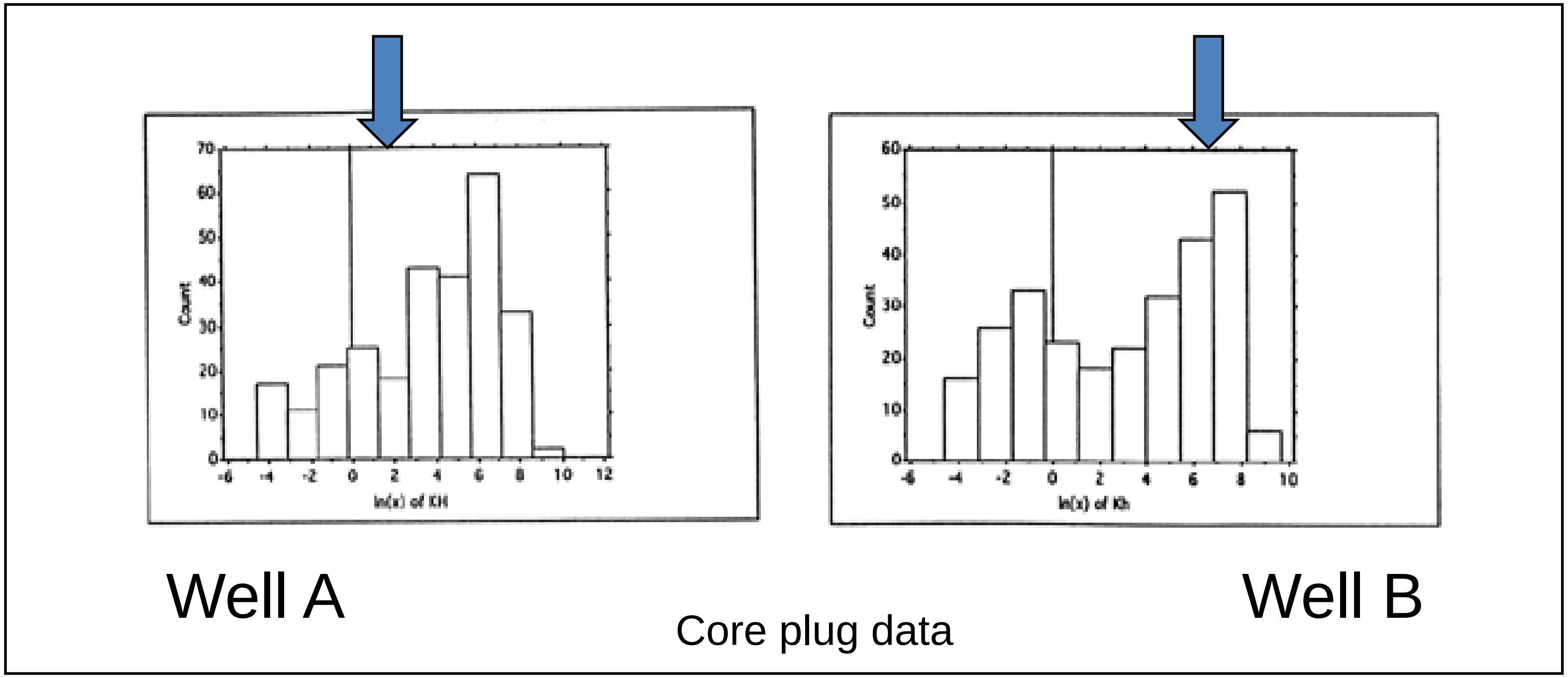
Comparing the well test and core perms.





- Need to consider the nature and scale of the layering in the volume of investigation of a well test

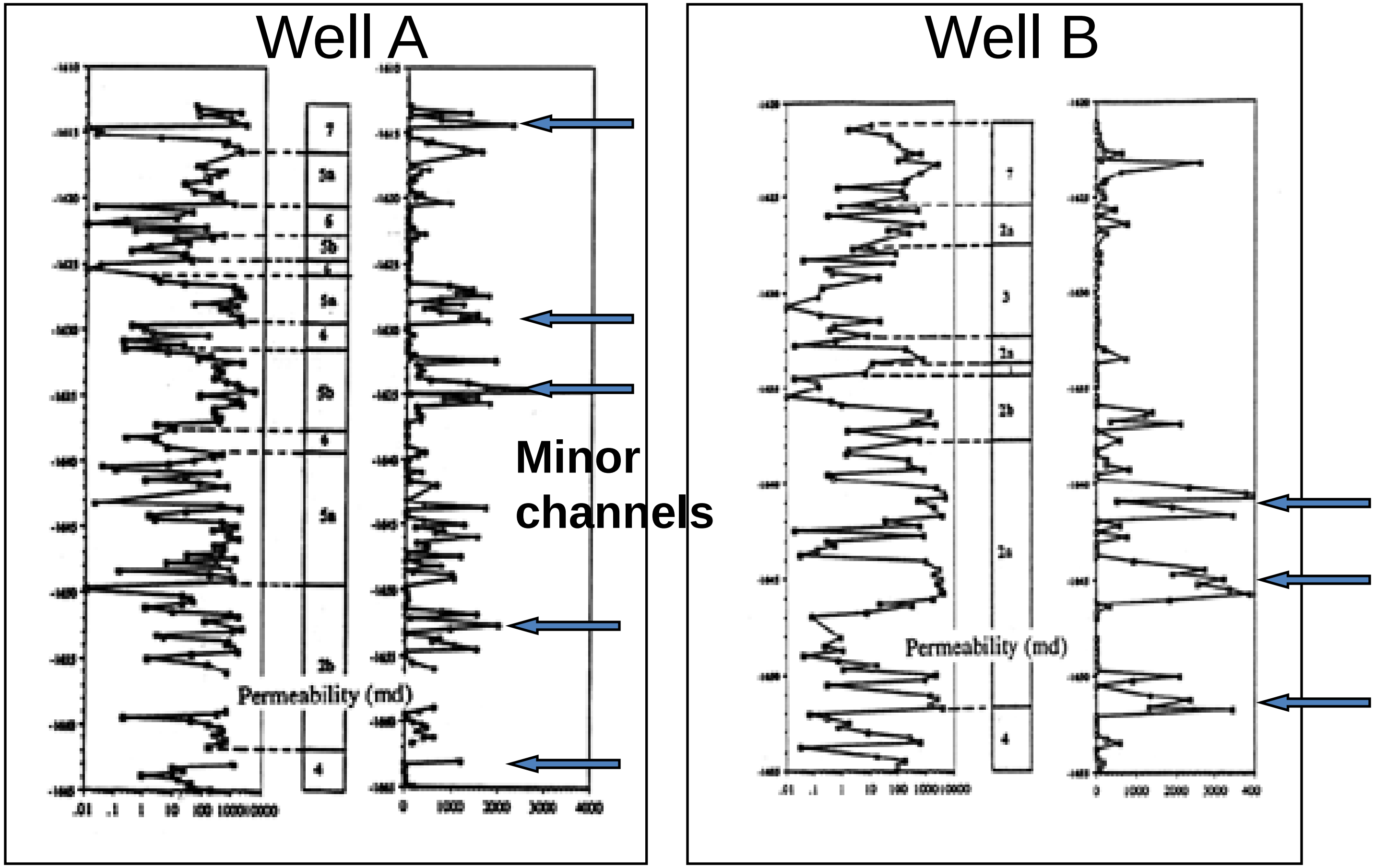
Well test comparison example



- Well A: Kar =400md ktest = 43md kgeom = 44md
- Well B: Kar =600md ktest = 1000md

Toro-Rivera et al., 1994

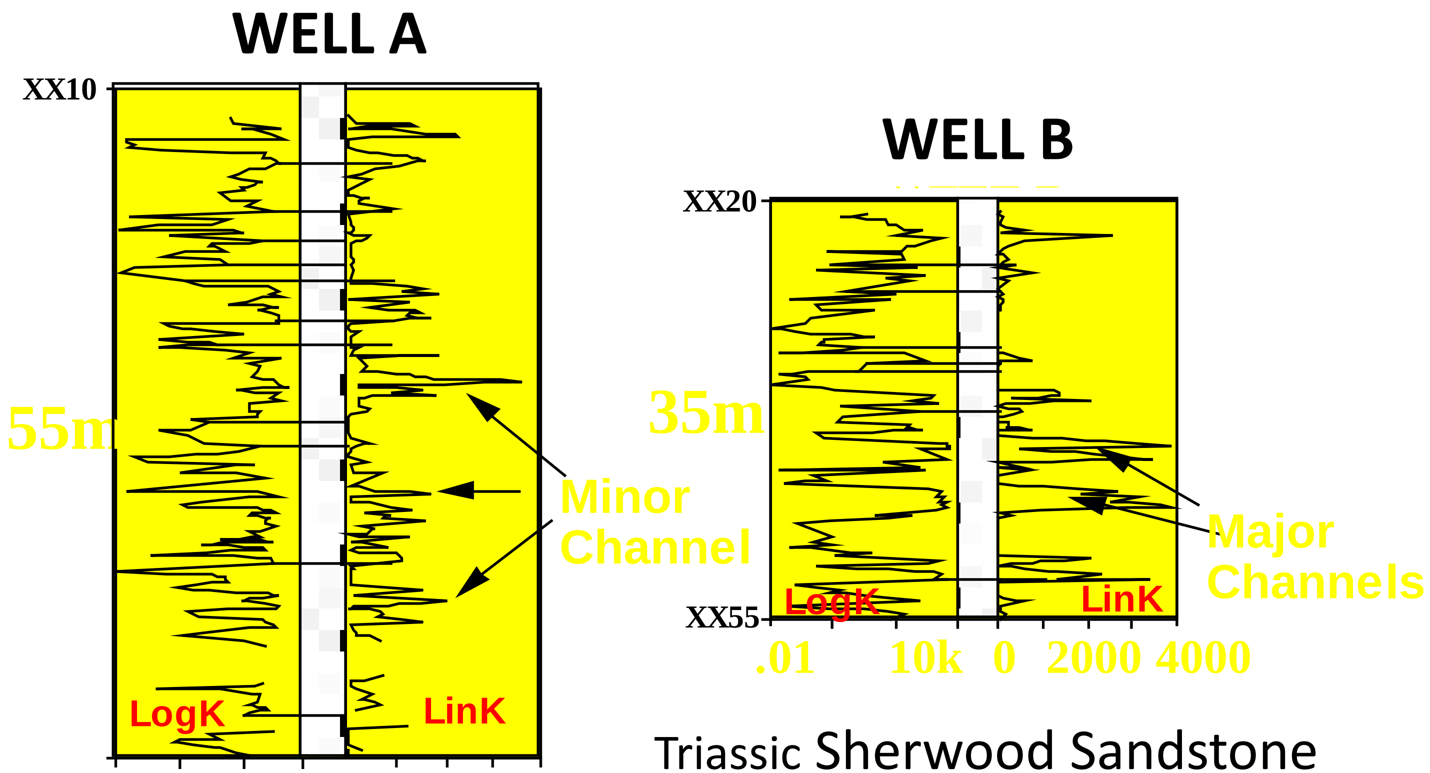
Permeability distributions in well



Major channels

- NB: K data plotted on log AND linear scales

Well test comparison example

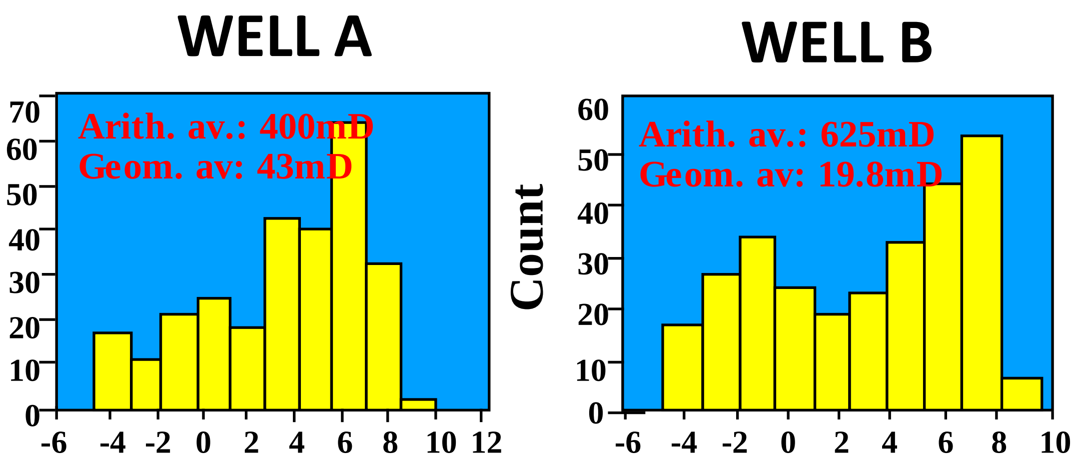


Triassic Sherwood Sandstone

Braided fluvial system

(Toro Rivera, 1994,SPE 28828, Dialog article)

Core plug petrophysics



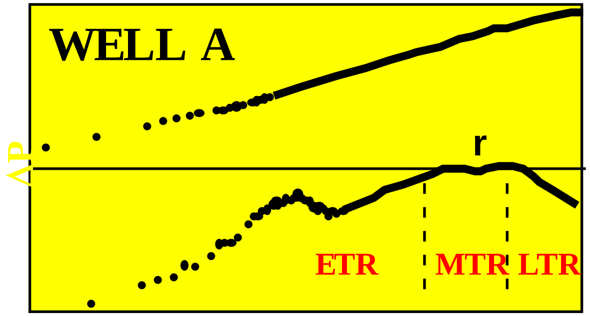
Permeability distributions similar

Permeability averages similar

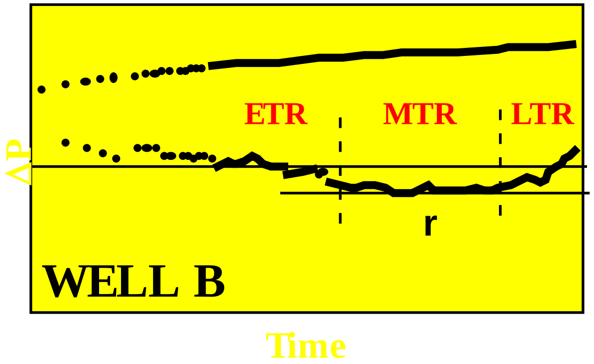
Effective permeability similar?

WT log-log plot

WELL A



WELL B

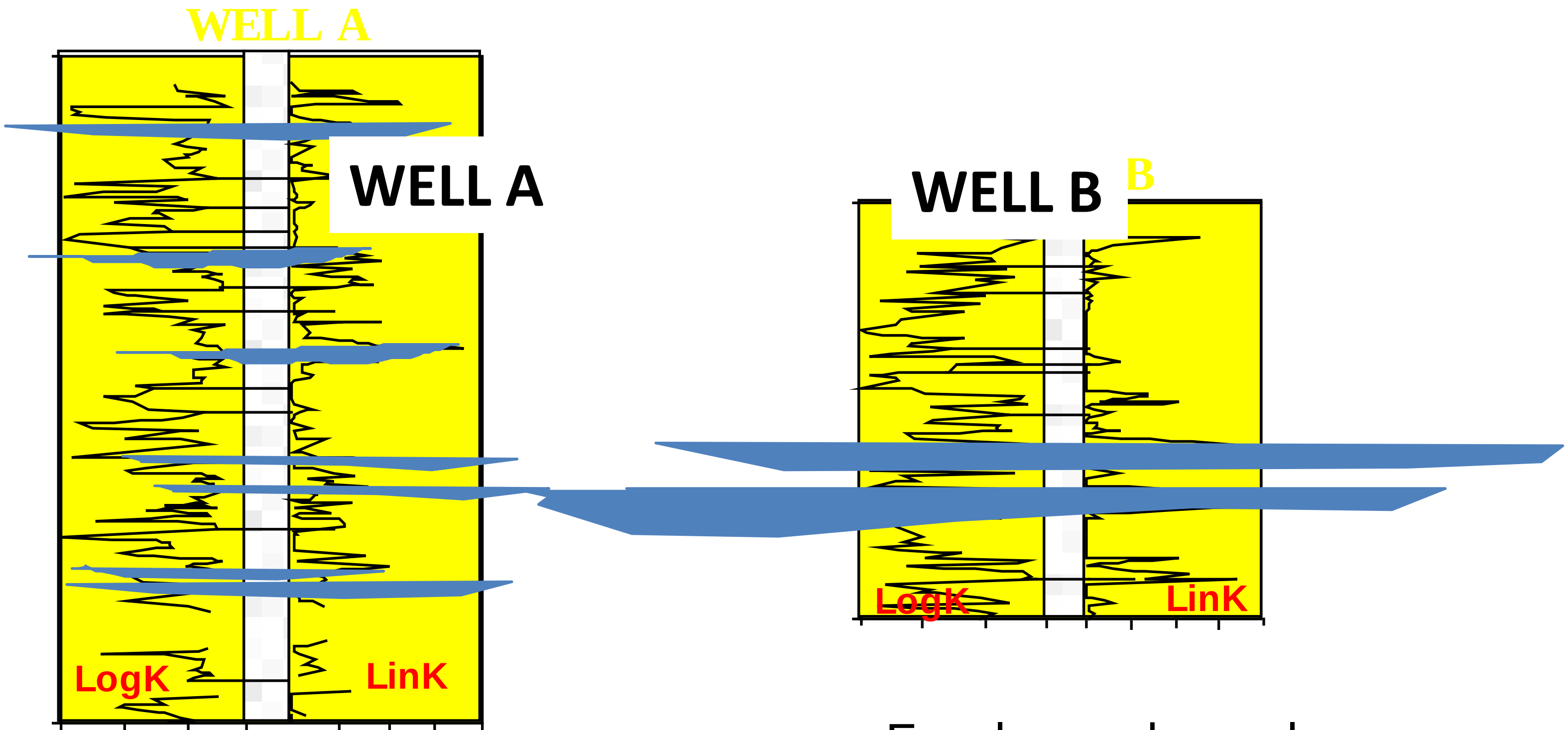


ETR: Linear flow
MTR: Radial flow (44mD)
Negative skin
LTR: OWC effect

ETR: Radial flow?
MTR: Radial flow (1024 mD)
Small positive skin
LTR: Fault?

Well test response very different
Geological interpretation?

Well Test Informed Geological Interpretation

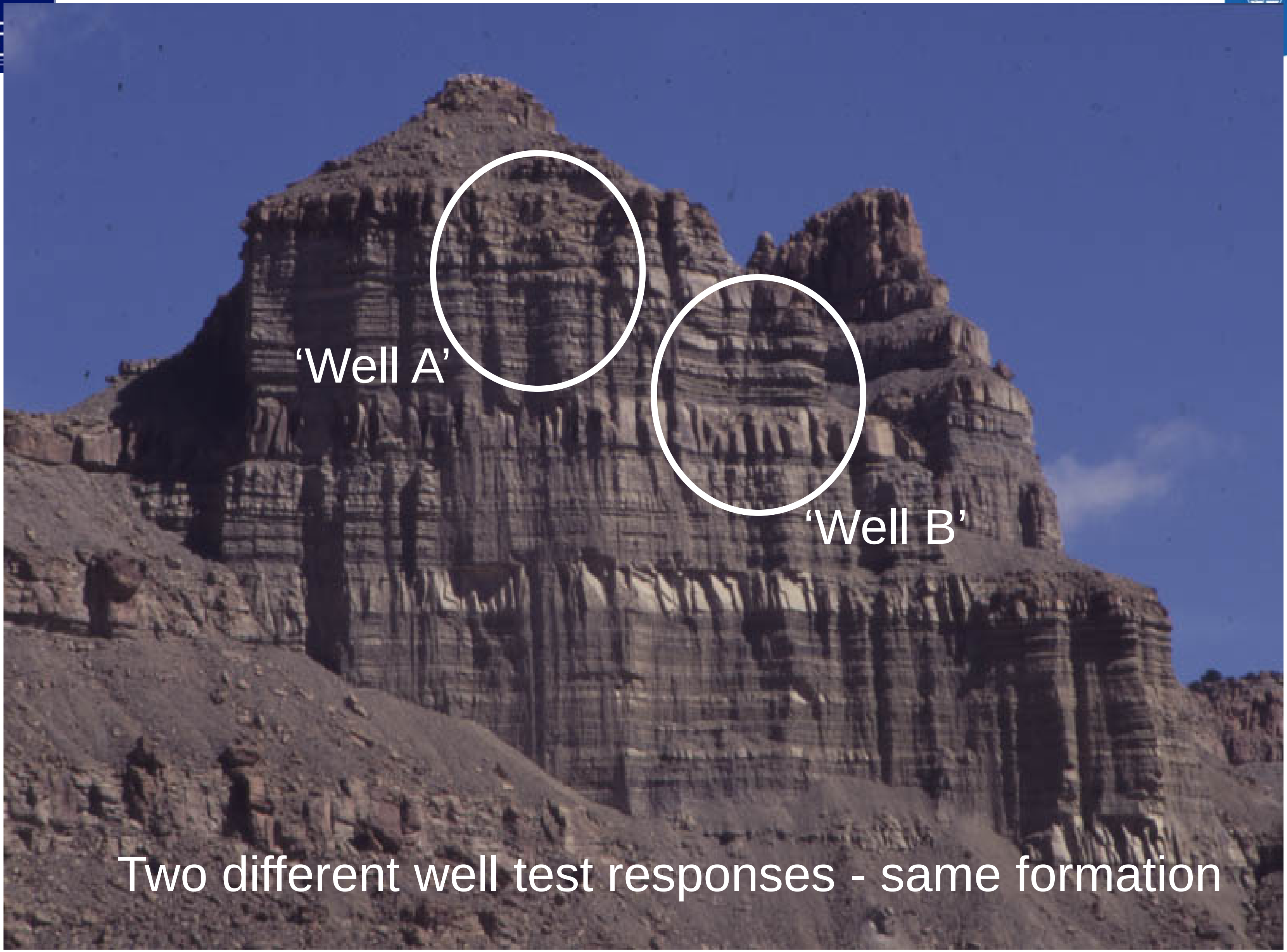


Many small channels
Limited extent
“Floodplain effective flow”

Few large channels
More extensive
“Channel effective flow”

INTERFLUVE

INCISED VALLEY


'Well A'
'Well B'
Two different well test responses - same formation

Coefficient of variation

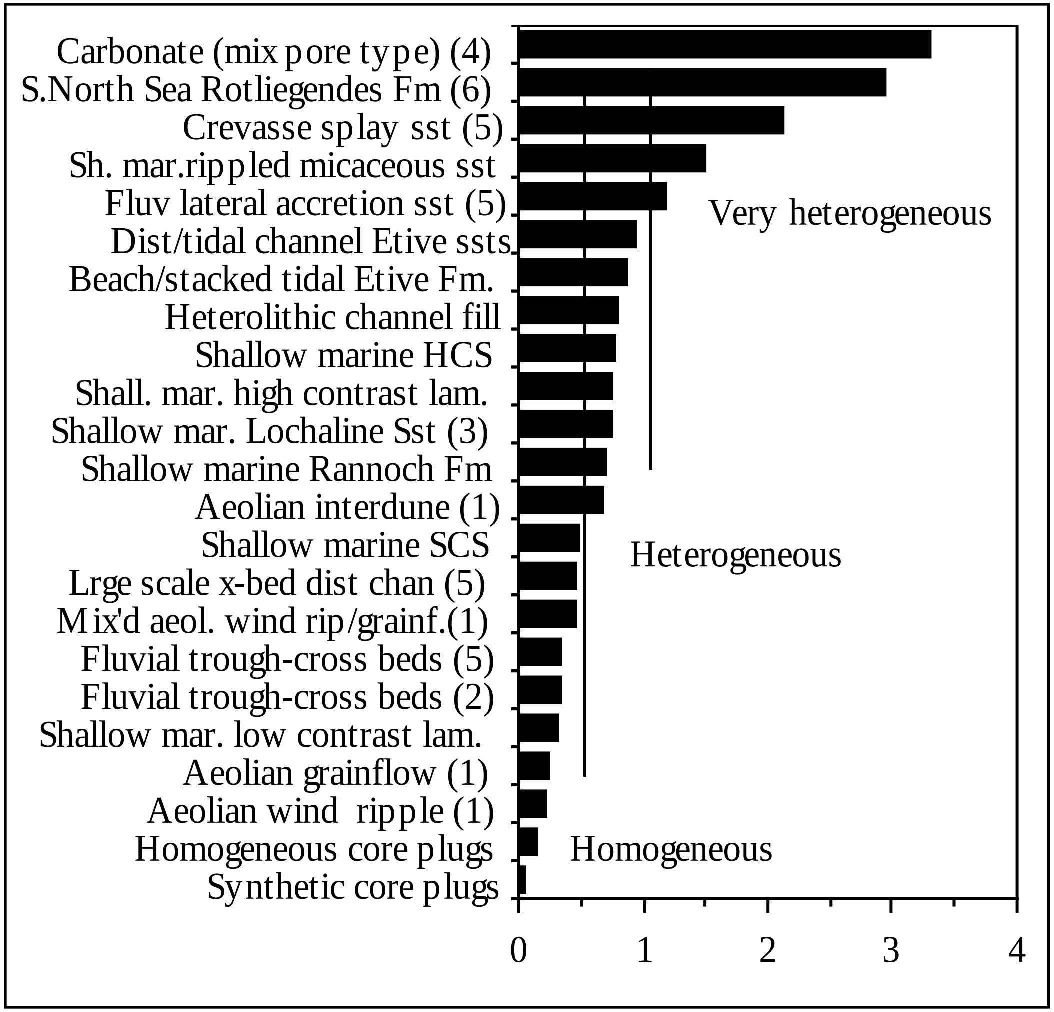
- Normalised measure of variability

$$Cv = \frac{SD}{\overline{k}_{ar}}$$

0 < Cv < 0.5 Homogeneous

0.5 < Cv < 1 Heterogeneous

1 < Cv Very Heterogeneous



Cv < 0.5 for a normal distribution

Sample sufficiency

- Representivity of sample sets
- for a tolerance (P) of 20%
- and 95% confidence level
- N_{zero} or N_o = optimum no. of data points

$$N_0 = (10 \bullet Cv)^2$$

- Where N_s = actual no. of data points
- P_s gives the tolerance

$$P_s = \frac{(200 \bullet Cv)}{\sqrt{N_s}}$$

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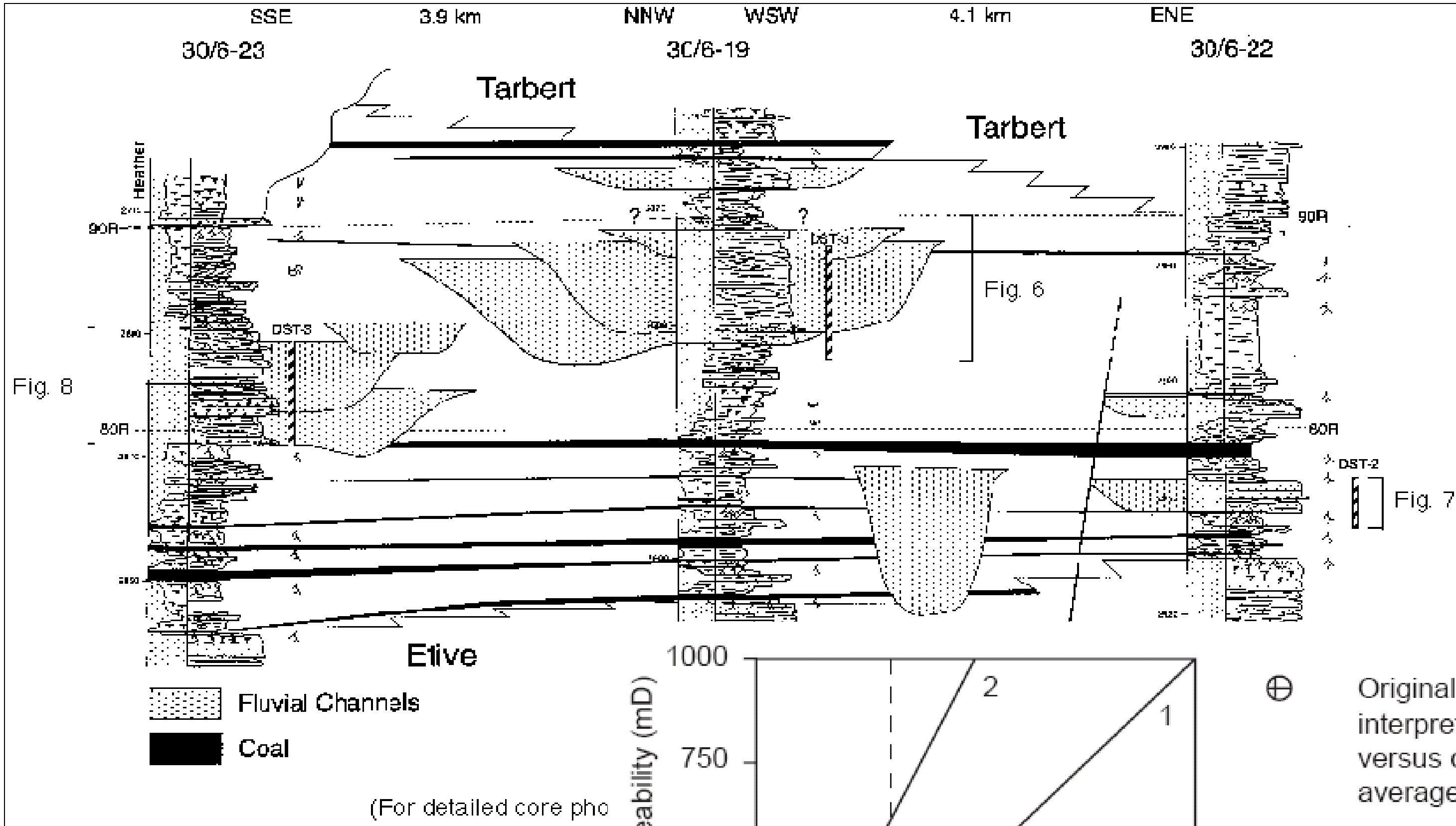
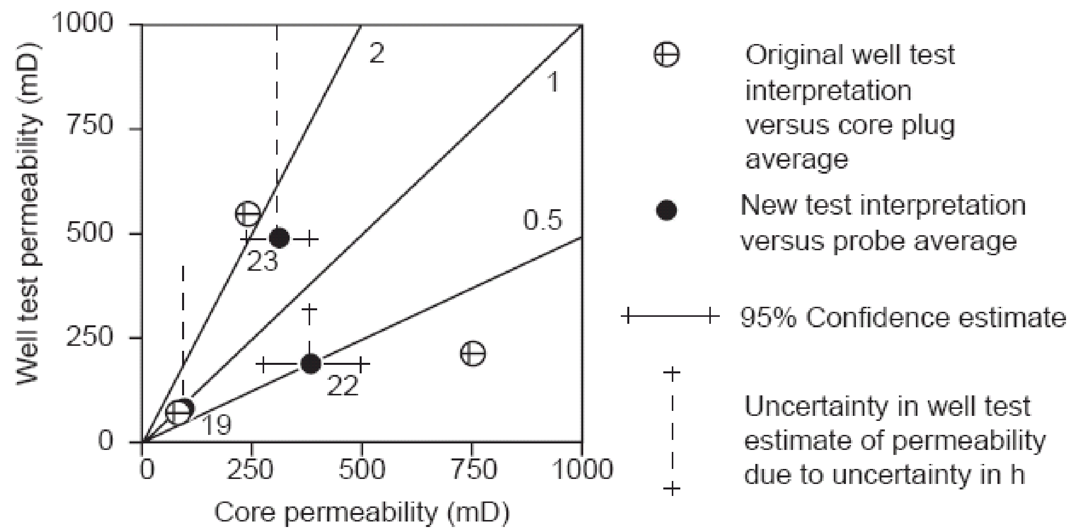
For carbonates (high variability P=50%) $N_0 = (4 \bullet Cv)^2$

Comparison of Core and Test Perms





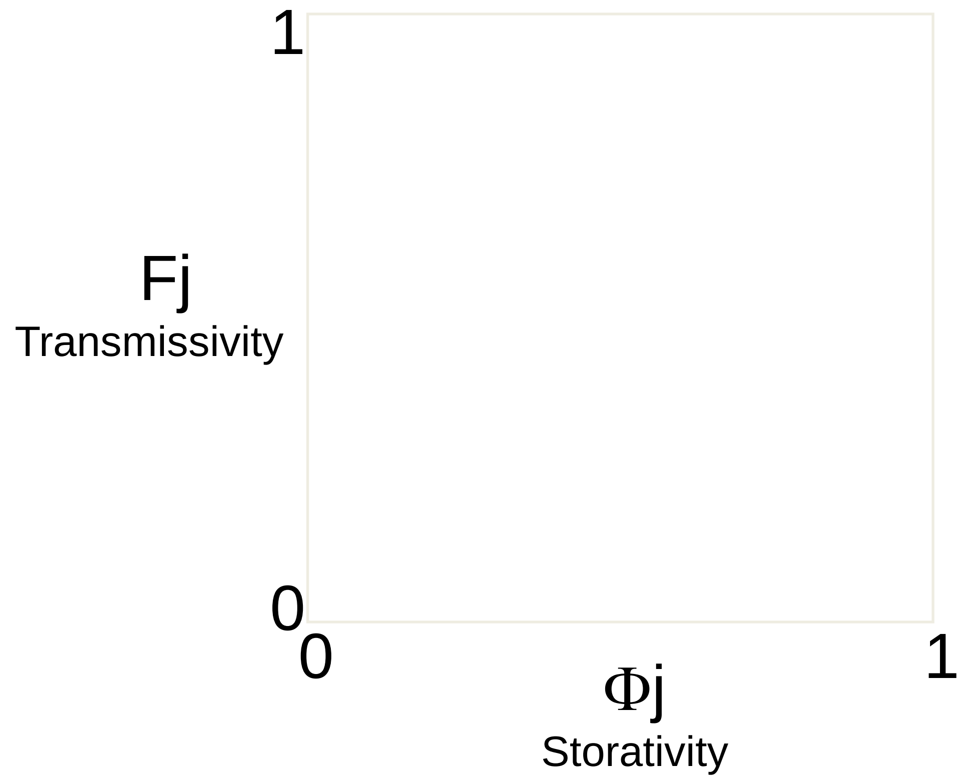
Zheng et al., 2000

Lorenz plot

- Order data in decreasing k/ϕ and calculate partial sums

$$Fj = \sum_{j=1}^{J} k_j h_j \Big/ \sum_{i=1}^{I} k_i h_i$$

$$Cj = \sum_{j=1}^{J} \phi_j \mathrm{h}_j \Big/ \sum_{i=1}^{I} \phi_i h_i$$



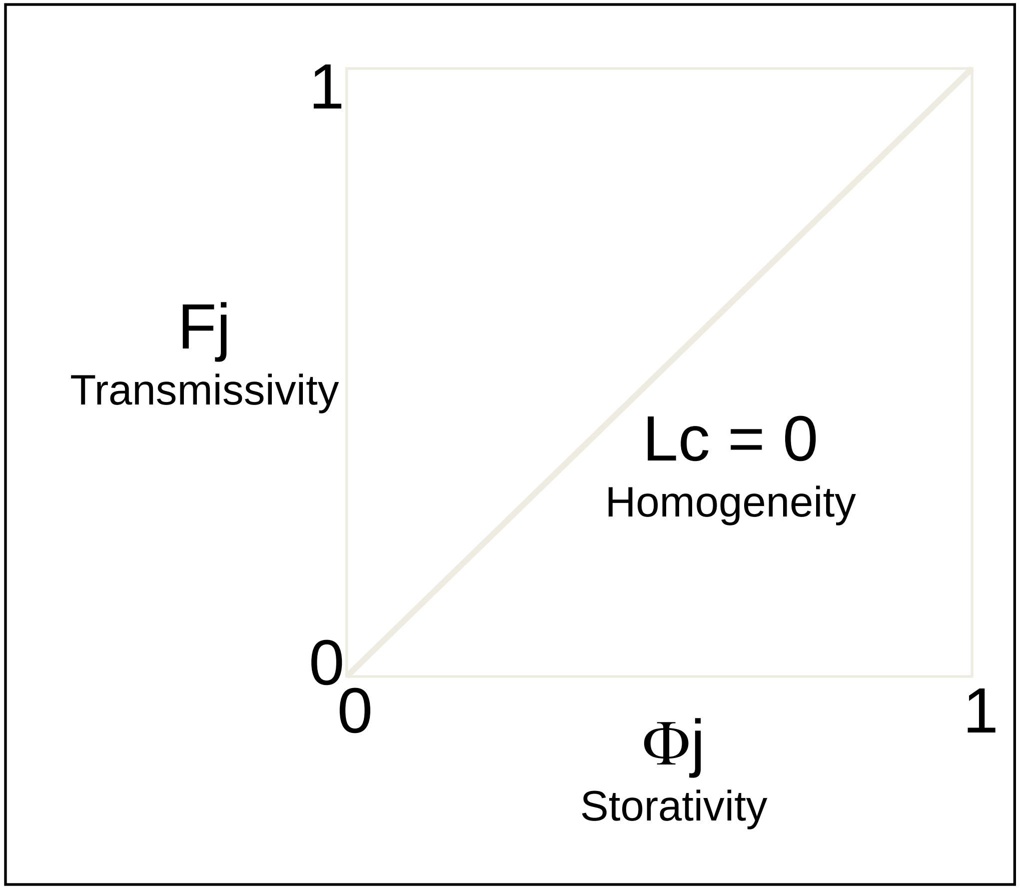
I = no. of data points

Lorenz plot

- Order data in decreasing k/ϕ and calculate partial sums

$$Fj = \sum_{j=1}^{J} k_j h_j \Big/ \sum_{i=1}^{I} k_i h_i$$

$$Cj = \sum_{j=1}^{J} \phi_j \mathrm{h}_j \Big/ \sum_{i=1}^{I} \phi_i h_i$$

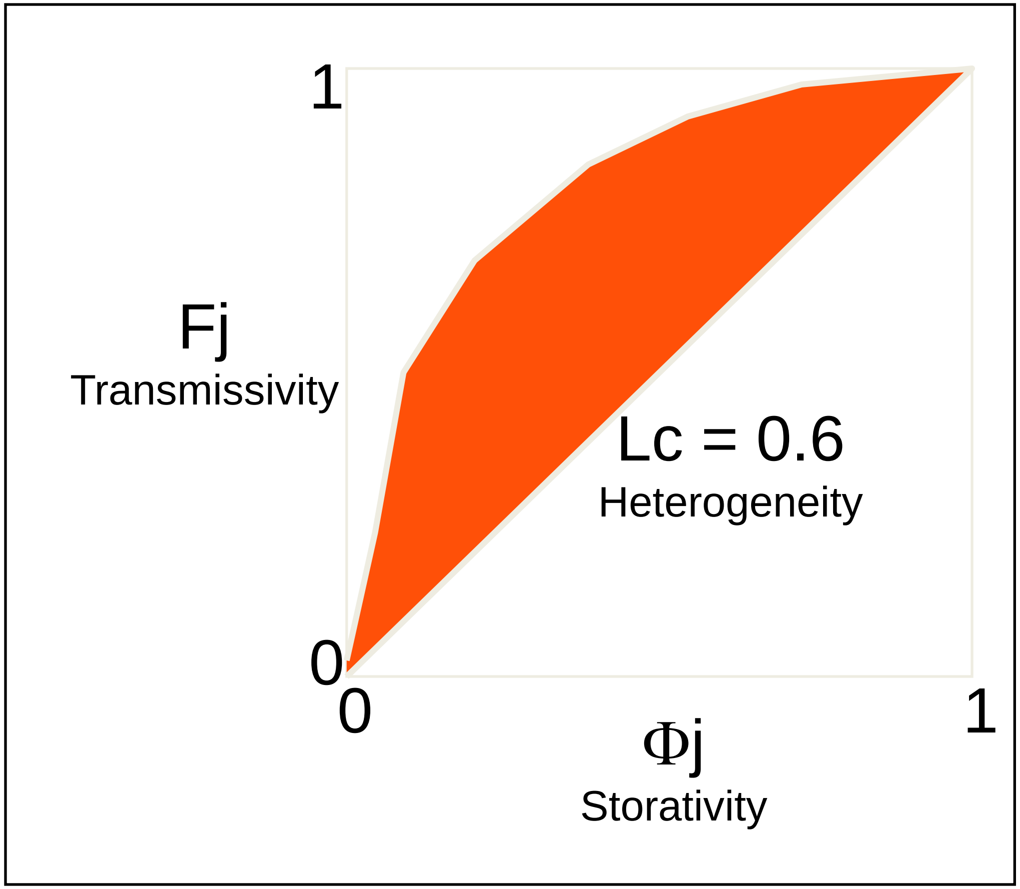


Lorenz plot >> Lorenz Coefficient

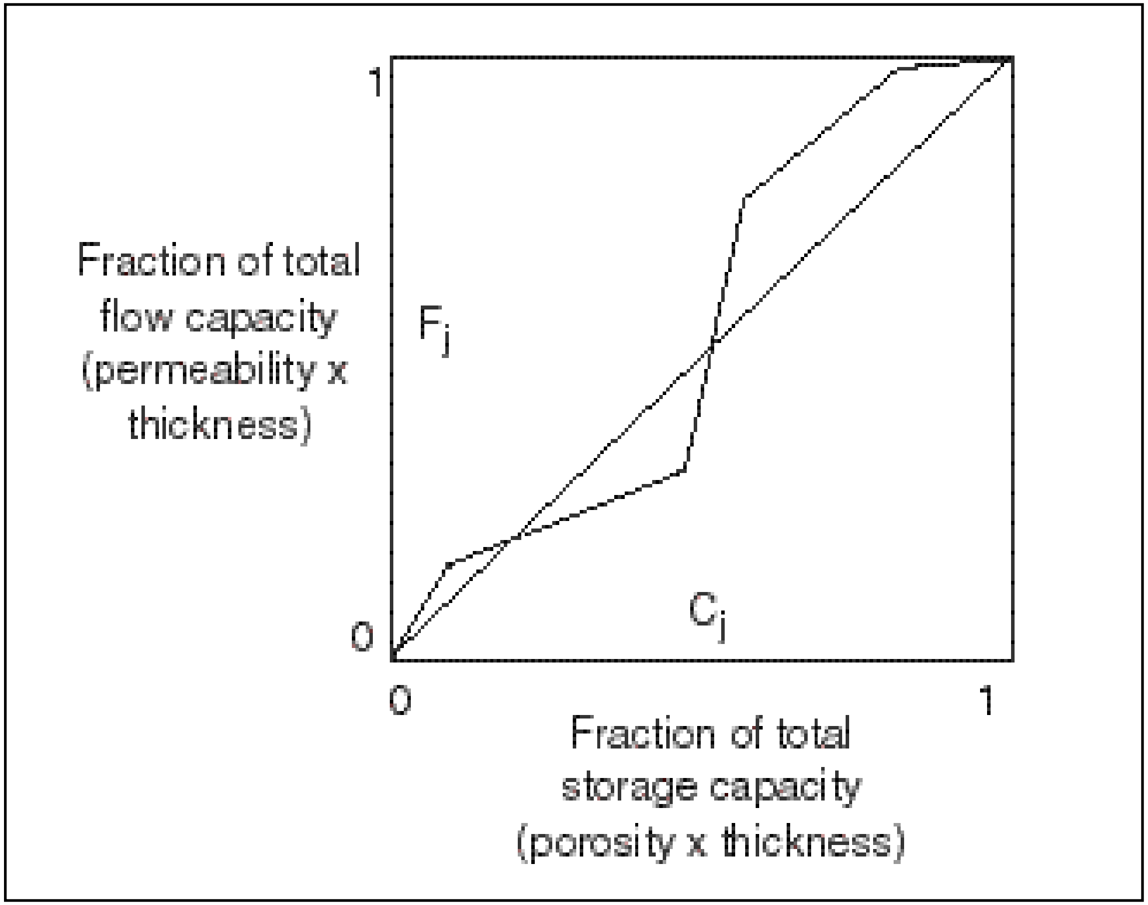
- Order data in decreasing k/ϕ and calculate partial sums

$$Fj = \sum_{j=1}^{j} k_j h_j \Big/ \sum_{i=1}^{i} k_i h_i$$

$$Cj = \sum_{j=1}^{j} \phi_j \mathrm{h}_j \Big/ \sum_{i=1}^{i} \phi_i h_i$$

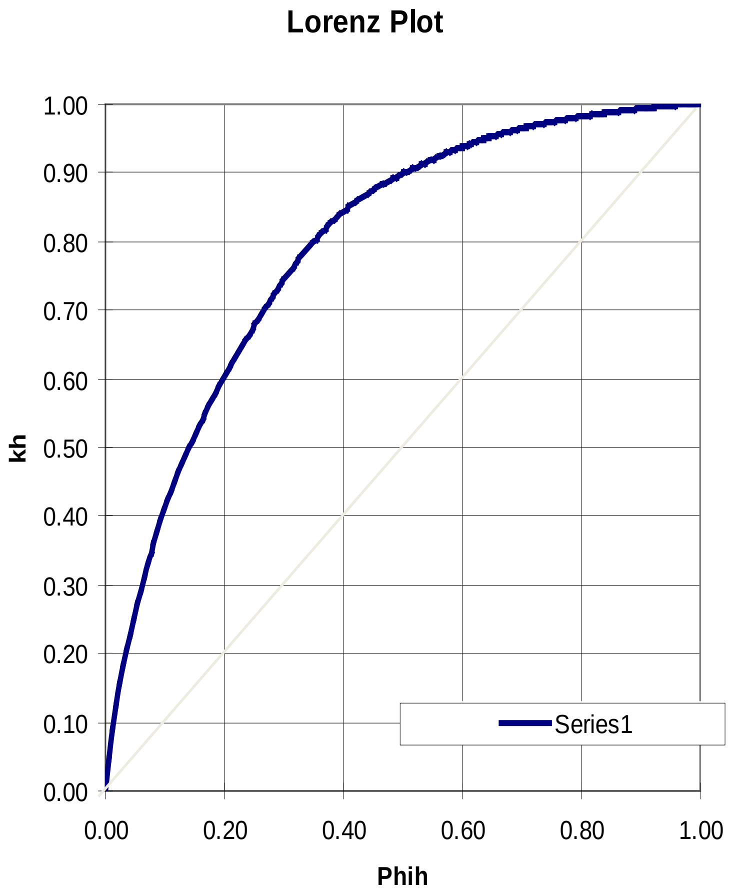


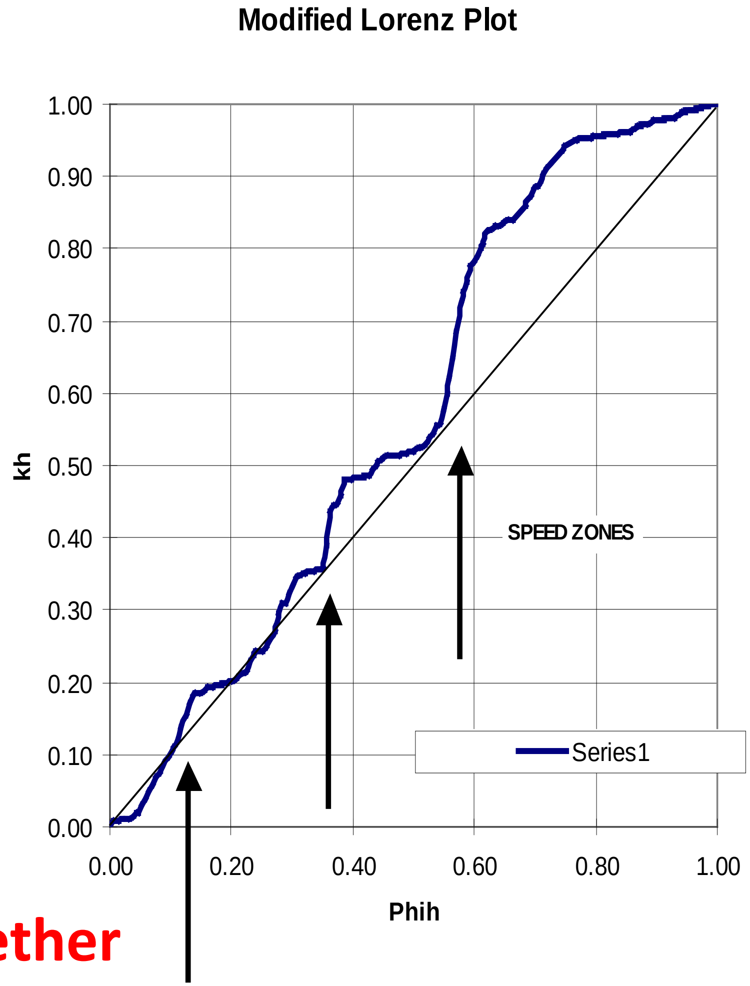
Unordered Lorenz Plot



Reveals stratigraphic layering

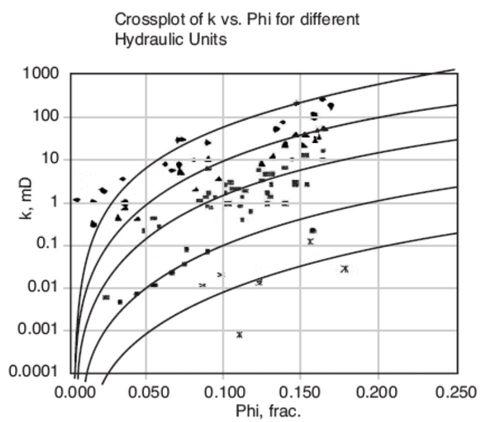
Example Lorenz Plots

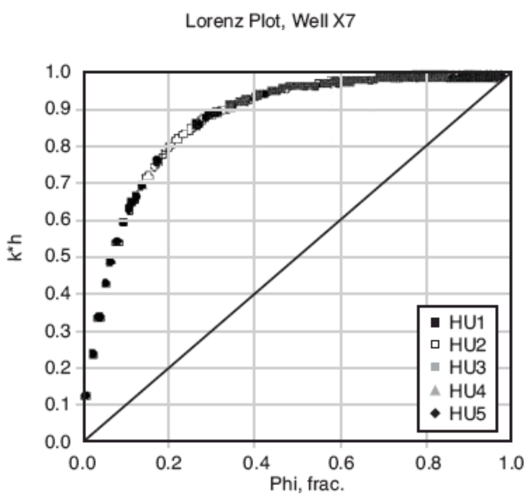


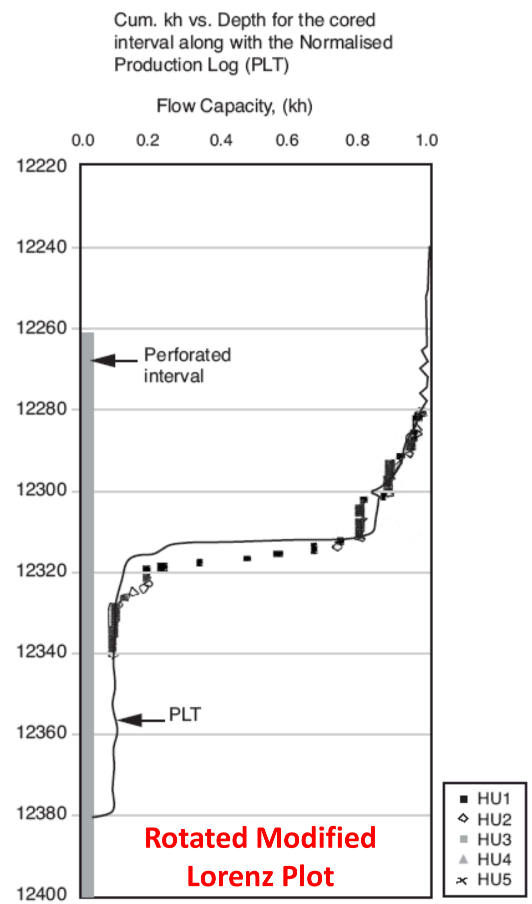


Use them together

Hydraulic Units and Heterogeneity







(Ellabed et al., 2001)

Heterogeneity and Anisotropy

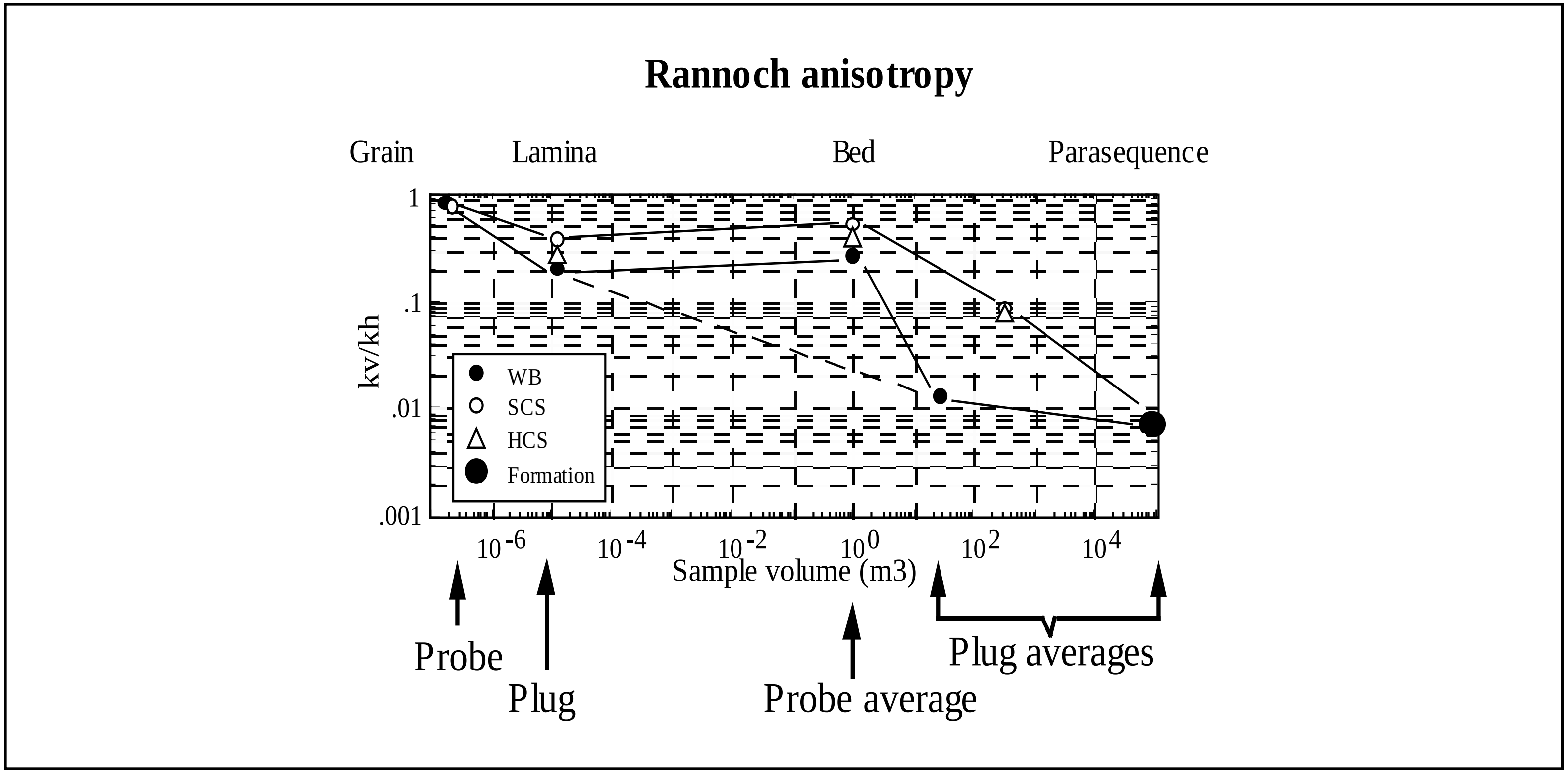
Increasing Heterogeneity →

k=constant	$Cv \leq 0.5$	$0.5 < Cv < 1.0$	$Cv \geq 1$
"Uniform"	"Homogeneous"	"Heterogeneous"	"Very Heterogeneous"

$k_v = k_h$ $(k_x = k_y = k_z)$	$\frac{k_v}{k_h}$ = constant	$\frac{k_v}{k_h}$ = variable
"Isotropic"	"Uniformly Anisotropic"	"Variably Anisotropic"

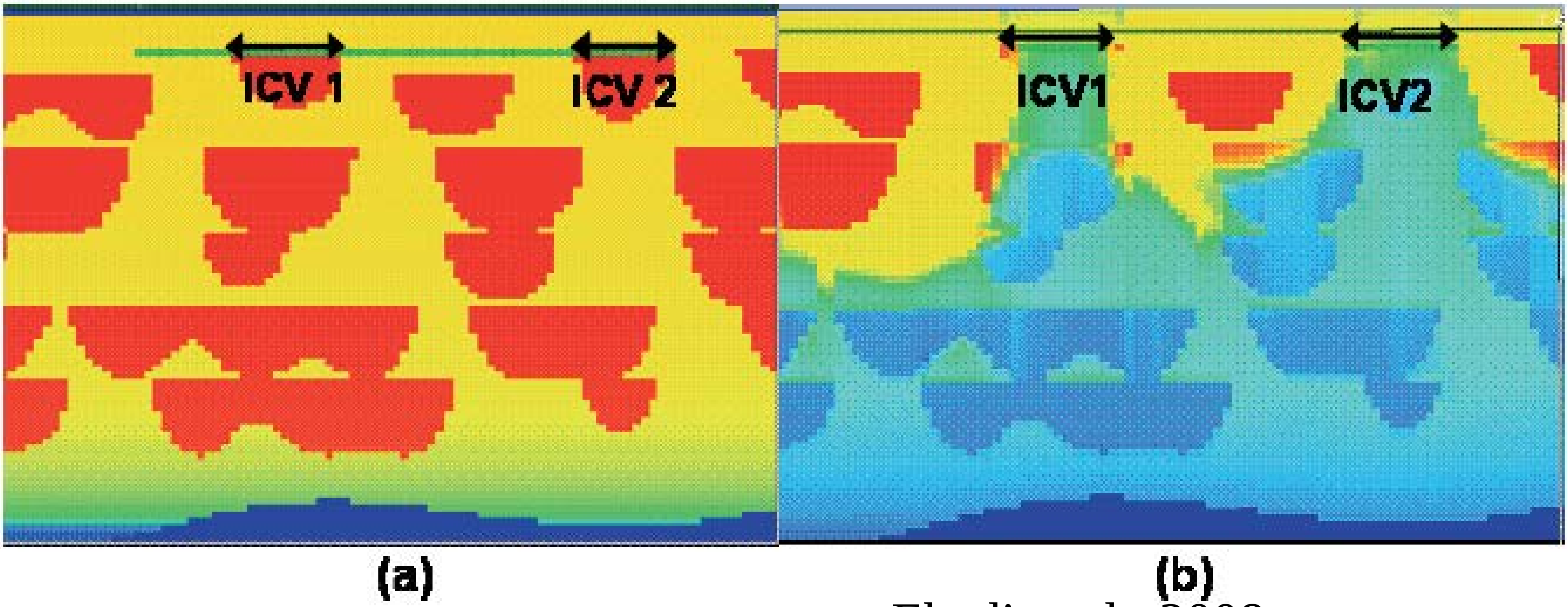
k_h = horizontal permeability h_v = vertical permeability
k_x, k_y, k_z = orthogonal permeabilities in a simulater
Cv = permeability coefficient of variation

Scale dependant anisotropy



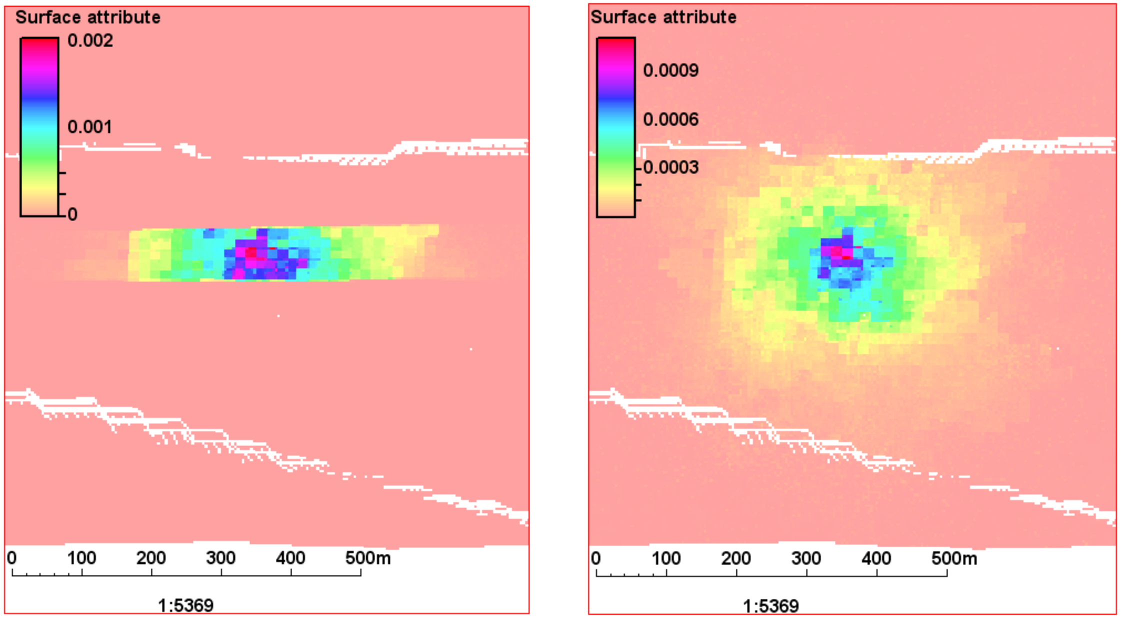
Estimate of kv/kh anisotropy depends on the scale of application

Kv controls vertical inflow



Ebadi et al., 2008

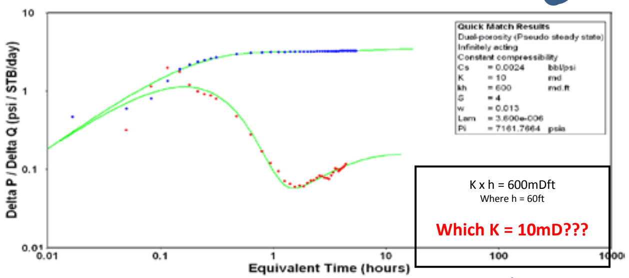
ICV – Interval Control Valve



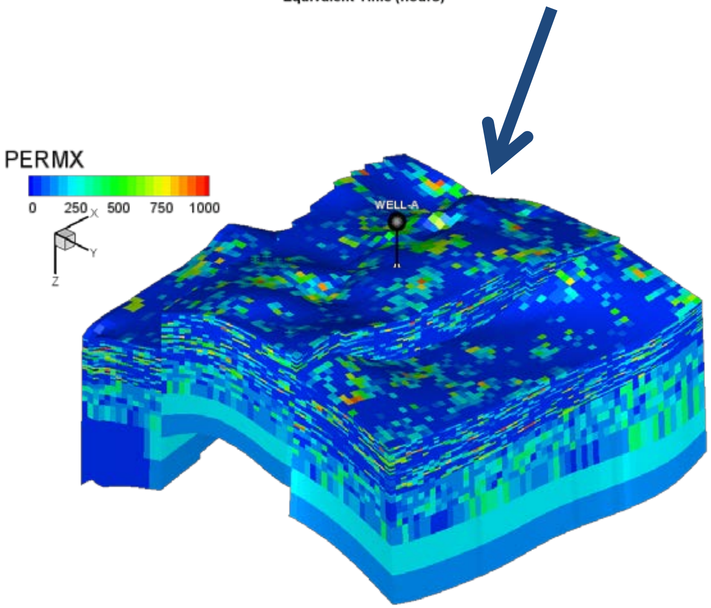
Putting it all together

Conclusions

- Well testing
  - Model driven
  - Simple Models
  - Averaging process



- Reservoir Description
  - Heterogeneous
  - Scale dependant
  - Upscaling challenge



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